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DEFENCE R&D DÉFENSE

Reference Temperature Determination for ASTM A517 and X80 Grade Steels

D.A. Hull

Engineering Material Research

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35 Carl Hall Road
Downsview, ON M3K 2B6

Contract #W7707-9-7201

Contract Scientific Authority Dr J. Morrison, 250-363-2924

Defence R&D Canada

Contractor Report
DREA CR 2001-177
November 2001

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Canada

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This report describes research and development contract work carried out on behalf of the DREA Dockyard Laboratory (Pacific) under Work Unit 1gh32 (Marine Steels).
Scientific Authority Dr J. Morrison.

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Abstract

This report describes the determination of reference temperatures for two steel plates and one weld, using ASTM Test Method E1921-97 "Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range" to generate transition master curves. Welded ASTM A517 steel is used in the Canadian Navy's Halifax class frigates, and both plate and a submerged arc weld have been tested in different orientations and at both quasi-static and intermediate loading rates. Plate samples of X80 steel from two different manufacturers have also been investigated. X80 steel is a candidate material for future use in the repair and construction of naval vessels.

This work is being supplemented by experiments at the Dockyard Laboratory (Pacific) using a drop tower to achieve higher deformation rates. The test program has been successful in quantifying the fracture toughness over the temperature range of interest. The materials studied were very tough, and had very low reference temperatures, suggesting a high resistance to brittle fracture.

Résumé

Ce rapport décrit le processus de détermination des températures de référence de deux plaques d'acier et d'une soudure au moyen de la méthode d'essai E1921-97 de l'ASTM « Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range » dans le but de produire des courbes de transition types. L'acier soudé ASTM A517 est utilisé dans les frégates de la classe Halifax de la marine canadienne. Les plaques et une soudure à l'arc submergée ont été mises à l'essai selon différentes orientations et à des taux de charge quasi-statiques et intermédiaires. Des échantillons de plaques d'acier X80 provenant de deux fabricants différents ont aussi été mis à l'essai. L'acier X80 est une option possible pour les réparations et la construction futures de navires de guerre.

À ces travaux viennent s'ajouter des expériences menées par le laboratoire du chantier naval (Pacifique) au moyen d'une tour d'essais de chute pour obtenir des taux de déformation plus élevés. Le programme d'essai a permis de quantifier la ténacité dans la gamme de températures voulue. Les matériaux mis à l'essai étaient très résistants et avaient des températures de référence très basses ce qui laisse supposer une résistance élevée aux ruptures fragiles.

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Executive summary

The primary method for avoiding brittle fracture in welded structures such as warship hulls is to prevent crack initiation by using high standards of quality control and workmanship during construction, particularly in welding. However, given normal shipyard limitations, some welds will likely have local regions of low toughness or small crack like defects. These could threaten the integrity of the structure if it encountered a suitably high combination of applied loading, stress concentration, and residual stresses. This necessitates very conservative estimates of tolerable flaw size to ensure ship safety unless the material toughness can be accurately quantified, and shown to be sufficiently high such that brittle fracture will not occur.

In recent years the availability of better instrumentation and a more sophisticated understanding of the fracture process has improved small specimen test methods for toughness determination. These not only yield more accurate toughness estimates, but also provide a better statistical description of data variability than was previously possible. As a result more cost effective structural integrity assessments can be made. Previous work showed that the procedure which was followed generated useful data on marine steels, and the Dockyard Laboratory (Pacific) is developing a database of fracture toughness values for all of the steels and welds of interest to the Canadian Navy. The results to date suggest that, under normal ship operating conditions, there is only a low risk of brittle fracture in the steels so far investigated.

Hull, D.A., 2001. "Reference Temperature Determination for ASTM A517 and X80 Grade Steels". Contract 2001-177. Defence Research Establishment Atlantic.

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Sommaire

La meilleure façon d'éviter les ruptures fragiles dans les structures soudées comme les coques des navires de guerre est de prévenir l'amorce des fissures en appliquant des normes rigoureuses de contrôle de la qualité et d'exécution lors de la construction et plus particulièrement lors du soudage. Cependant, étant donné les limites des chantiers de construction navale, certaines soudures comporteront probablement des zones de ténacité moindre ou de petits défauts ressemblant à des fissures qui peuvent menacer l'intégrité de la structure si elles sont soumises à une combinaison suffisamment élevée de charges appliquées, de concentration de contraintes et de contraintes résiduelles. La taille des défauts doit donc être évaluée avec prudence pour assurer la sécurité du navire, à moins que la ténacité du matériau puisse être évaluée avec précision et jugée suffisamment élevée pour qu'il ne puisse y avoir de rupture fragile.

Depuis quelques années, des instruments plus performants et une meilleure compréhension du processus de rupture ont permis d'améliorer les méthodes d'essais sur petites éprouvettes pour déterminer la ténacité. Ces méthodes ont non seulement permis d'obtenir des évaluations de ténacité plus précises mais aussi de fournir une meilleure description statistique de la variabilité des données, ce qui n'était pas possible auparavant, et ainsi d'effectuer des évaluations moins coûteuses de l'intégrité structurale. Des travaux antérieurs ont démontré que la procédure utilisée permettait de recueillir des données utiles sur les aciers de qualité marine. Le laboratoire du chantier naval (Pacifique) travaille à l'élaboration d'une base de données sur les valeurs de ténacité de toutes les soudures et de tous les aciers utilisés par la marine canadienne. Jusqu'à maintenant, les résultats démontrent que dans des conditions de fonctionnement normales, il n'y a qu'un faible risque de rupture fragile dans les aciers étudiés.

Hull, D.A., 2001. Reference Temperature Determination for ASTM A517 and X80 Grade Steels. DREA CR 2001-177 Defence Research Establishment Atlantic.

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1.0 INTRODUCTION

The development of improved fracture control procedures for Canadian warships will allow selection of materials possessing high structural integrity to maximize operational readiness and reduce life-cycle maintenance costs. The Dockyard Laboratory Pacific (DL(P)) has an on-going requirement to determine the fracture toughness of ferritic steels and welds in the ductile to brittle transition temperature range. The ASTM Test Method E1921-97 "Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range" is being used to develop transition curves characterized using maximum likelihood statistics by a reference temperature at a K_{Jc} toughness value of 100 MPa$\sqrt{m}$.

CSA G21 350WT is a ferritic steel used extensively in the hulls of the Canadian Navy's Halifax class frigates. A Phase I contract (W7708-7-0705, Reference 1) demonstrated that valid results could be obtained from 15 mm thick 350WT specimens using the ASTM standardized test method. The effect of orientation and loading rate on the same 350WT plate and on the fusion zone toughness of a 9 mm thick submerged arc welded plate was investigated during a Phase II contract (W7707-8-6178, reference 2). These results could then be integrated with the Phase I data as part of a growing material property database.

This report describes Phase III of this DL(P) sponsored research program. The objectives of this particular segment were a) to extend the previous work to include an ASTM A517 steel plate and submerged arc weld, and b) to evaluate X80 grade plate from different manufacturers. ASTM A517 is a high strength steel used in selected areas (i.e. the flight decks) on the Halifax class frigate decks. X80 plate is a steel developed primarily for applications such as pipeline construction, but which is also of interest as a potential low cost marine construction material. The plates investigated were procured by DL(P) from IPSCO in Canada (designated X80-A) and BHP in Australia (designated X80-B). The effect of plate orientation (L-T and T-L) and loading rate (quasi-static and intermediate) on the toughness of these materials was investigated for comparison with the Phase I and II results. Engineering Material Research carried out these fracture toughness measurements under research and development contract W7707-9-7201.

2.0 TEST PROCEDURE

The 9 mm thick X80 and A517 plates had the chemical compositions shown in Table I, and the original test matrix is presented in Table 2. The ASTM A517 plate had a longitudinal submerged arc butt weld, and the test specimens were cut transverse to this weld so that a full-thickness crack ran along the weld centre-line. Two displacement rates (0.05 and 6 mm/s) were used to give nominal elastic stress intensity rates averaging 8 MPa$\sqrt{m}$/s (quasi-static) and 700 MPa$\sqrt{m}$/s (intermediate rate) respectively. The single edge notched bend specimens which were machined at DL(P) had nominal dimensions of 9 x 30 x 130 mm. This is a deviation from the more usual Bx2B cross sectional geometry (where B is specimen thickness), but the Phase II work had

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established that this did not affect the measured Reference Temperatures. The welded specimens were cut transverse with the notch in the centre of the fusion zone.

Tensile test properties at each fracture test temperature were needed for data qualification purposes. Subsized flat tensile specimens that met ASTM Standard Test Method E8-98 requirements were machined from rectangular full thickness blanks supplied by DL(P). In the case of welded samples the tensiles were cut with their long axis transverse to the weld. The yield strength (0.2% offset), ultimate tensile strength, and elongation to fracture were all determined experimentally.

The bend specimens were pre-cracked to a nominal a/W of 0.5 at ambient temperature, and then side-grooved 10% of the thickness on each side. In welded samples residual stresses can result in uneven fatigue crack growth across the specimens width. To try to minimize this effect, before precracking a lateral plastic precompression of 1% of the width was applied to each side along the ligament ahead of the notch. This worked fine for welds, but interestingly, when inadvertently used on some A517 L-T plate samples it produced uneven crack fronts.

The low temperature tests were conducted using a 100 kN capacity servo-hydraulic load frame with a 100 mm wall thickness insulated cold box within which temperatures down to –120C could be maintained to within ±2°C during testing. The specimens were mounted on a stainless steel three point bend fixture inside the cold box. The flow of liquid nitrogen from a cryogenic dewar into the cold box was regulated using a temperature controller to cycle a solenoid valve. Load was measured using the crosshead mounted load cell, and specimen crack mouth opening displacement (CMOD) was obtained using a clip gauge. A personal computer controlled the load frame operation and acquired data. The specimen temperature was monitored using two thermocouples spot welded within 5 mm of the specimen starter notch tip on each side.

The test temperatures ($T = T_{28J} + C$, where the constant C depends on specimens thickness) were selected initially per ASTM E1921-96 guidelines using energy values from Charpy V-notch specimen test data supplied by DL(P). After trial tests were completed the test temperature could then be adjusted as required. This procedure is suitable only for tests carried out at quasi-static loading rates. For faster tests it is a matter of judgement to make an appropriate increase in test temperature based on the results of the quasi-static series. The standard requires that a cleavage instability occur at test temperature, and the target median K_{Jc} is 100 MPa$\sqrt{m}$. A minimum of six replicate specimens must be tested, and up to six more specimens were available to permit additional testing in the event this proved to be statistically necessary. The bend specimens were cooled to the test temperature and dwelled for 3-5 minutes before the test was started. Two displacement rates (0.05 and 6 mm/s) were used to give the desired average elastic stress intensity rates using a ramp waveform. Following completion of the fracture test, the broken halves of the specimen were removed from the test rig and heated to approximately 50°C to remove condensation from the fracture surfaces, and were then air cooled. Crack lengths were measured with an optical travelling microscope using the nine point average procedure of ASTM E1921-97. For this particular specimen geometry, the nine crack length measurements must not differ from the average by more than 7%.

The required cleavage event must occur prior to reaching the K_{Jc} capacity the specimen given by

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the equation:

$$K_{Jc(limit)} = \sqrt{(E\, b_o \sigma_{ys} / 30)} \qquad (1)$$

Where E is the elastic modulus, σ_{ys} is the yield strength at test temperature and loading rate, and b_o is the specimen remaining ligament length.

Plots of load versus CMOD were constructed, and the data used to calculate J-integral values using the expressions provided in the standard. The transition temperature curve was determined using the maximum likelihood procedure also provided in the standard, and a typical curve with upper (5%) and lower (95%) tolerance bounds is shown in Fig. 1. For any given set of specimens, major variations in the amount of non-linear deformation (plasticity) can be expected before an instability occurs, as can be observed in the load-displacement curves. Figure 2 shows four possible categories that were arbitrarily defined to describe the full range of possible material behaviour. In practice, only three of these were observed during these particular tests. In the following sections the amount of plasticity observed for each test is indicated using Types I-III to describe elastic, elastic-plastic, and near limit load behaviour respectively.

3.0 RESULTS

3.1 Tensile Tests.

Tensile load versus displacement plots are given in Appendix A. Yield strength, ultimate tensile strength, and elongation are shown in Table 3. Failure of the parent material in the cross-weld specimens indicated the weld is stronger than the plate. Plate tensile results were used with equation (1) to determine the specimen K_{Jc} capacities listed in Table 4.

3.2 K_{Jc} Tests.

For each set of test specimens master curve calculations are summarized in Tables 5-21 Crack size determinations and detailed K_{Jc} calculations, are tabulated in Appendix B. The individual load versus CMOD displacement curves generated during the fracture tests are shown in Appendices C - J.

3.2.1 X80-A Plate.

a) L-T Orientation – Intermediate Loading Rate (Tables 5-6, B1-B2, Appendix C).

Exploratory testing using quasi-static loading rates yielded results that consistently exceeded the K_{Jc} capacity of the specimen at temperatures down to –100°C. As a result, the X80 steels were only tested at the intermediate loading rate. Ten tests at –95°C gave valid results (Table 5). A fracture event resulting in greater than a 5% decrease in force was considered to be a crack instability, presumably triggered by a cleavage event. The specimen fracture surface met the crack front straightness requirements. The fracture force varied between 10.8 and 16.9 kN and

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K_{Jc} values ranged from 127 to 325 MPa$\sqrt{m}$. Three specimens exceeded the K_{Jc} capacity limit of 260 MPa$\sqrt{m}$, so that a censored E1921-97 data analysis was used, whereby the K_{Jc} capacity limit is substituted for any higher results. A median K_{Jc} value of 183 MPa$\sqrt{m}$ and a reference temperature of –136°C were calculated using thickness adjusted K_{Jc}(1T) values (Table 6). The transition temperature curves and limits are shown in Figure 3. The roman numeral paired with each data point in the figure indicates the type of load versus displacement material behaviour as defined in Figure 1. Figure 3 contains Types I to III. In these specimens the growing crack remained in the side grooves at the surface, but tended to deviate leaving either a hump or a depression towards the plate mid-thickness on opposite sides of the crack.

b) T-L Orientation – Intermediate Loading Rate (Tables 7-8, B3-B4, Appendix D).

Six tests were carried out at –95°C and these valid results are presented in Table 7. Crack instabilities occurred at forces ranging between 10.6 and 13.6 kN, and K_{Jc} values varied from 98 to 125 MPa$\sqrt{m}$. These results did not exceed the K_{Jc} capacity of 263 MPa$\sqrt{m}$, and produced a median K_{Jc}(1T) value of 88 MPa$\sqrt{m}$ with a reference temperature of –85°C (Table 8). The transition temperature curves are shown in Figure 4, and a relatively low scatter is evident. Only type I material behaviour was exhibited by these specimens. The crack front straightness requirements were met, but the crack surface ended with on a "sawtooth" or "corrugated" appearance.

The L-T and T-L fracture surfaces are shown in Figure 5. The difference in the reference temperatures between the two plate orientations was 51°C.

3.2.2 X80-B Plate.

a) L-T Orientation – Intermediate Loading Rate (Tables 9-10, B5-B6, Appendix E).

Exploratory quasi-static loading tests suggested that the K_{Jc} capacity limit of 264 MPa$\sqrt{m}$ would be exceeded, and so intermediate loading rate tests were conducted at –120°C. The crack front straightness requirements were met, and Table 9 shows that the force at crack instability varied from 8.6 to 13.6 kN, with K_{Jc} values between 96 and 285 MPa$\sqrt{m}$. The latter K_{Jc} value was replaced by the K_{Jc} capacity limit in a censored data analysis, and the K_{Jc}(1T) median was 161 MPa$\sqrt{m}$, with a reference temperature of –153°C (Table 10). Figure 6 presents the transition temperature curves and indicates that Types I and II material behaviours were observed. These specimens exhibited a similar out-of-plane "humped" fracture to that observed on the X80-A L-T specimens.

b) T-L Orientation – Intermediate Loading Rate (Tables 11-12, B7-B8, Appendix F).

Six tests were carried out at -110°C and the results are presented in Table 11. The fracture force values varied from 9.7 to 11.4 kN and K_{Jc} from 86 to 175 MPa$\sqrt{m}$. Crack front straightness limits were acceptable. Analysis of the valid data set gave a median K_{Jc}(1T) of 102 MPa$\sqrt{m}$, and a reference temperature of –111°C (Table 12). Individual results and the temperature transition curves are plotted in Figure 7. Only Type I material behaviour was observed at this test temperature. The fracture surfaces exhibited the corrugated appearance seen on the X80-A T-L

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specimens.

A difference of 42°C existed between the reference temperatures for the two X80-B plate orientations, and the X80-B plate reference temperatures were on average 22°C lower than those for the X80-A plate. The combined X80 A and B plate results are shown in Figure 8. Lower scatter in the T-L orientation was observed in both plates, and, although the fracture surfaces were very rough, the crack deviated less than in the L-T orientation. Micro-hardness measurements have also shown through-thickness variability in both of the X80 plates[3].

3.2.3 A517 Plate.

a) L-T Intermediate Loading Rate (Tables 13-15, B9-B10, Appendix G).

Intermediate loading rate tests were carried out at –120°C and these results are shown in Table 14. Specimens subjected to a compressive indentation applied to both sides of the specimen at the machined notch had increased crack front problems, and seven of the fourteen specimens tested failed to meet the ASTM standard. At the –120°C temperature, only Type I material behaviour was observed. The fracture force varied from 4.2 to 12.0 kN with K_{Jc} values between 73 and 229 MPa$\sqrt{m}$ (Table 14). The data were censored to the K_{Jc} capacity limit of 221 MPa$\sqrt{m}$, and the analysis included only specimens that met the crack front straightness requirement. A 142 MPa$\sqrt{m}$ median K_{Jc}(1T) and a –139°C reference temperature were calculated (Table 15). The transition temperature curves are plotted in Figure 9. Inclusion of all 14 specimens shifted the reference temperature upward by only 2°C.

b) T-L Intermediate Loading Rate (Tables 16-17, B11-B14, Appendix H).

Exploratory quasi-static loading rate tests were carried out at temperatures that ranged from –80 to -120°C. K_{Jc} varied from 177 to 308 MPa$\sqrt{m}$, and extensive plasticity was evident (Table 13), suggesting that a valid data set might only be obtained at a much lower temperature. However, six valid test results were then obtained at –110°C and the crack front straightness requirements were met. None of these specimens received the compression indent procedure. Table 16 shows that crack instabilities occurred at force and K_{Jc} values of 5.9 to 12.4 kN and 101 to 265 MPa$\sqrt{m}$ respectively. The latter K_{Jc} value was replaced by the 217 MPa$\sqrt{m}$ capacity limit of the specimen in the censored data analysis. The resulting median K_{Jc}(1T) of 146 MPa$\sqrt{m}$ and –136°C reference temperature (Table 17), and the transition temperature curves are shown in Figure 10. Only Type I material behaviour was observed.

There was only a 3°C difference in reference temperatures between the two plate orientations.

3.2.4 A517 Weld.

a) Quasi-Static Loading Rate (Tables 18-19, B15-16, Appendix I).

The welded specimens were evaluated at –80°C and Type I and II material behaviour was

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observed for these specimens. Two specimens did not meet the crack front straightness requirements and these specimens were excluded from further analysis. The force at crack instability varied from 7.2 to 9.3 kN and the corresponding K_{Jc} values ranged from 137 to 235 MPa$\sqrt{m}$. The latter value was replaced by the K_{Jc} limit of 199 MPa$\sqrt{m}$ using a censored data analysis. The median K_{Jc}(1T) was 138 MPa$\sqrt{m}$, with a reference temperature of –103°C (Table 19), and the temperature transition curves are presented in Figure 11. The scatter in these results was smaller than that observed for the plate specimens.

b) Intermediate Loading Rate (Tables 20-21, B17-B18, Appendix J).

The results of the intermediate loading rate tests carried out at –70°C are shown in Table 20. Two specimens did not meet the crack front straightness requirements and were excluded from data analysis. Fracture force ranged from 7.8 to 9.7 kN and K_{Jc} values from 139 to 202 MPa$\sqrt{m}$. The K_{Jc} capacity of 199 MPa$\sqrt{m}$ was substituted for the 202 MPa$\sqrt{m}$ value in a censored data analysis. A median K_{Jc}(1T) of 130 MPa$\sqrt{m}$ and a reference temperature of –89°C were determined (Table 21). Individual results and temperature curves are presented in Figure 12. Type I material behaviour was predominant, with a single Type II result. There is similar scatter to the quasi-static results.

Quasi-static and intermediate loading rate specimens had a 14°C difference in reference temperature. Combined plate and weld results are shown in Figure 13. Comparison of the weld and plate intermediate loading rate reference temperatures shows that the weld's reference temperature is 49°C higher than the plate.

3.3 Reference Temperature Summary

Material	Orientation	Loading Rate	Reference Temperature °C
X80-A Plate	L-T	Intermediate	-136
X80-A Plate	T-L	Intermediate	-85
X80-B Plate	L-T	Intermediate	-153
X80-B Plate	T-L	Intermediate	-111
A517 Plate	L-T	Intermediate	-139
A517 Plate	T-L	Intermediate	-136
A517 Weld	-	Quasi-static	-103
A517 Weld	-	Intermediate	-89

4.0 CONCLUSIONS.

The fracture toughness of X80 and A517 grade steels has been determined at temperatures where cleavage is the primary fracture mechanism using the ASTM E1921-97 test method. X80 reference temperatures at intermediate loading rates suggest that both batches have satisfactory

toughness at temperatures and loading rates that would be encountered during marine service. The X80-B steel had a higher toughness and lower reference temperature than steel A. The A517 steel plate exhibits reference temperatures that are comparable to the X80 steels but the weld reference temperature is significantly higher. ASTM A517 steel has virtually the same toughness in both the L-T and T-L orientations, whereas the X80 steels (like the previously tested CSA 350WT) are very directional in properties. These results can be used both to predict material behaviour in service, and also for ranking of candidate alloys for future construction.

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3. Dixon, T., McGowan, C., George, K.B., "Evaluation of BHP and IPSCO X80 Plate", DERA Report Tr990343/1.0.

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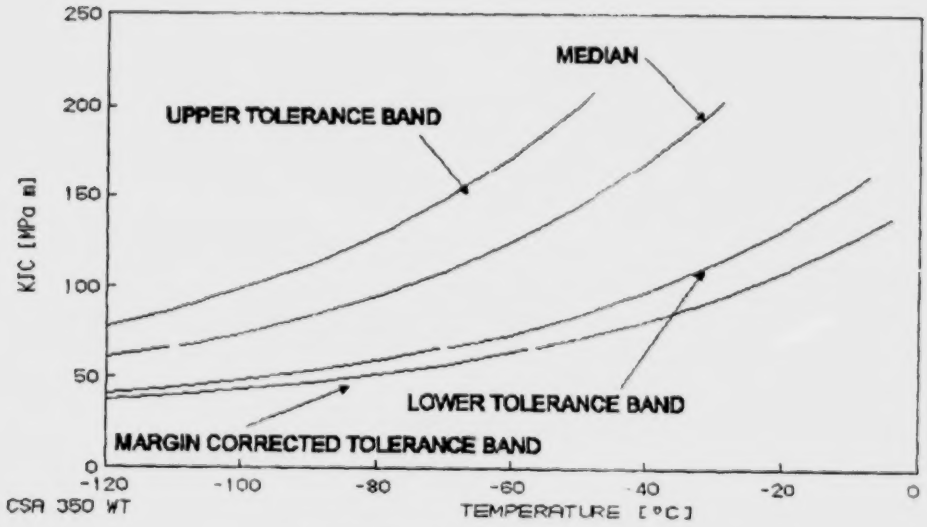

Figure 1 - Typical Master Curve And Tolerance Bands.

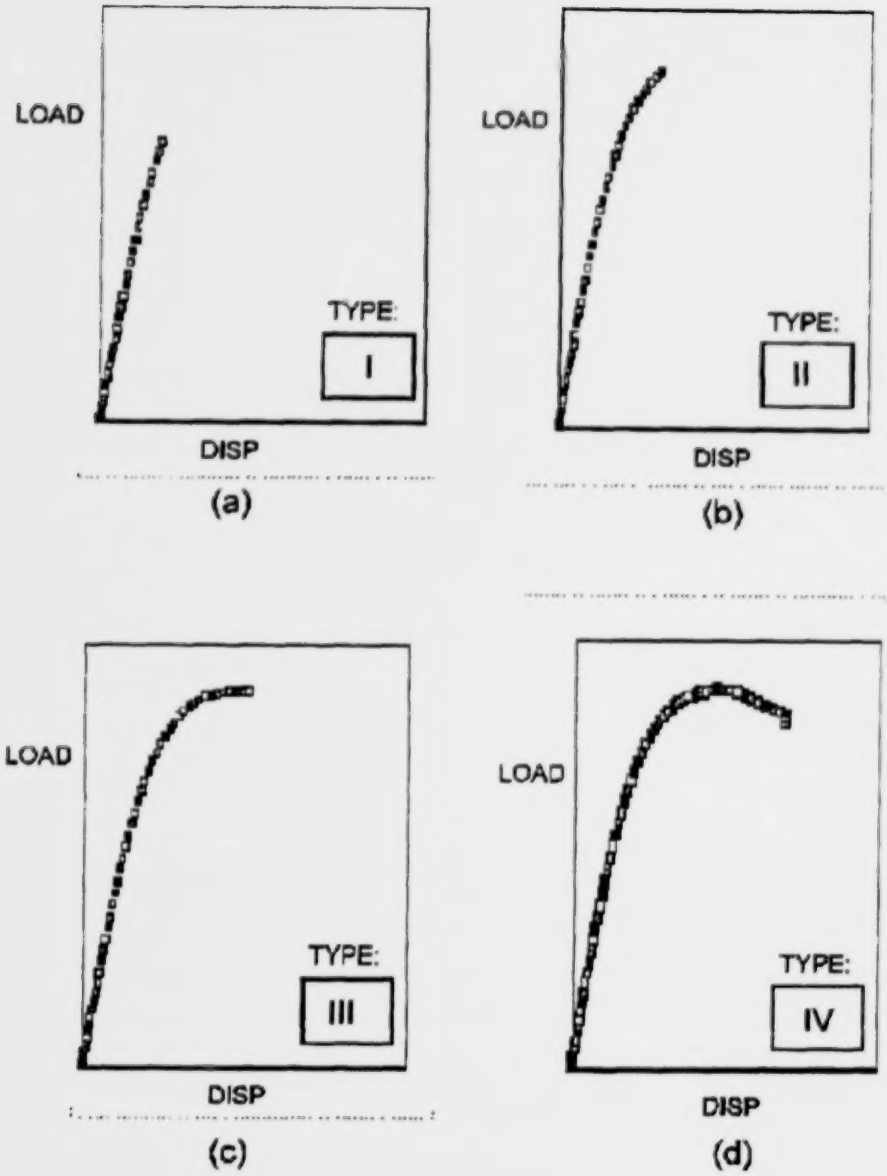

Figure 2.
Material Behaviour Indicated By
Load Vs. Displacement Plots:
(a) Elastic, (b) Elastic-Plastic Prior To Limit Load,
(c) Elastic-Plastic At Limit Load, and
(d) Elastic-Plastic Beyond Limit Load.

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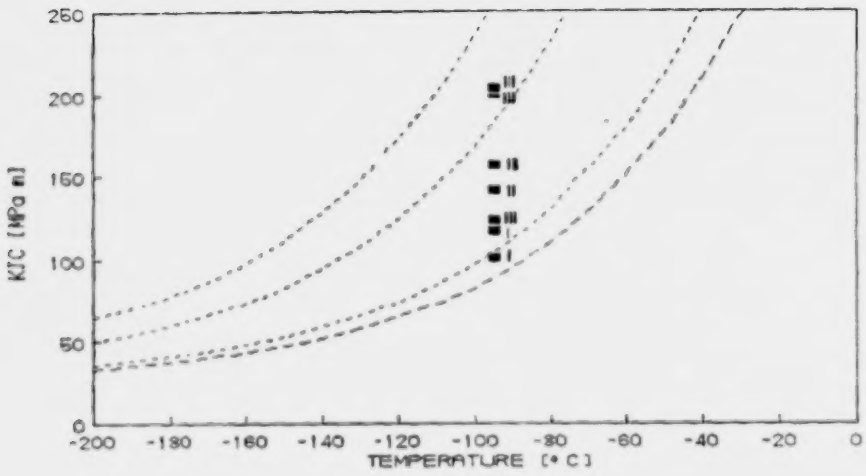

Figure 3 - X80-A L-T Master Curve.(Intermediate Loading at -95°C)

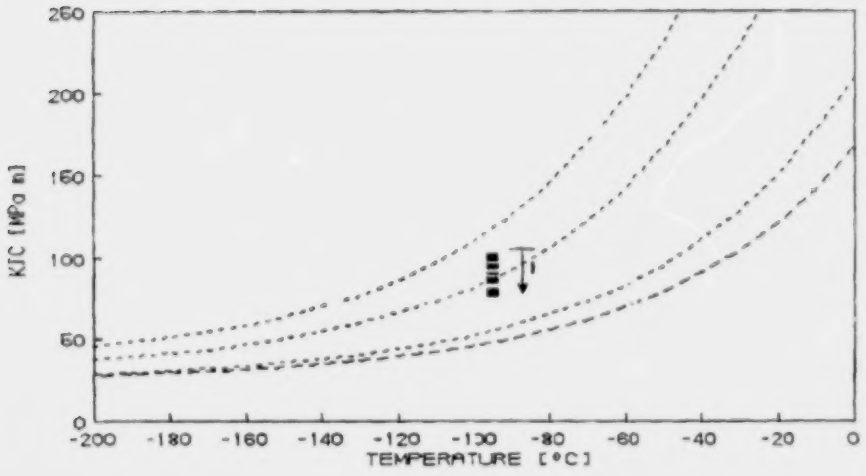

Figure 4 - X80-A T-L Master Curve.(Intermediate Loading at -95°C)

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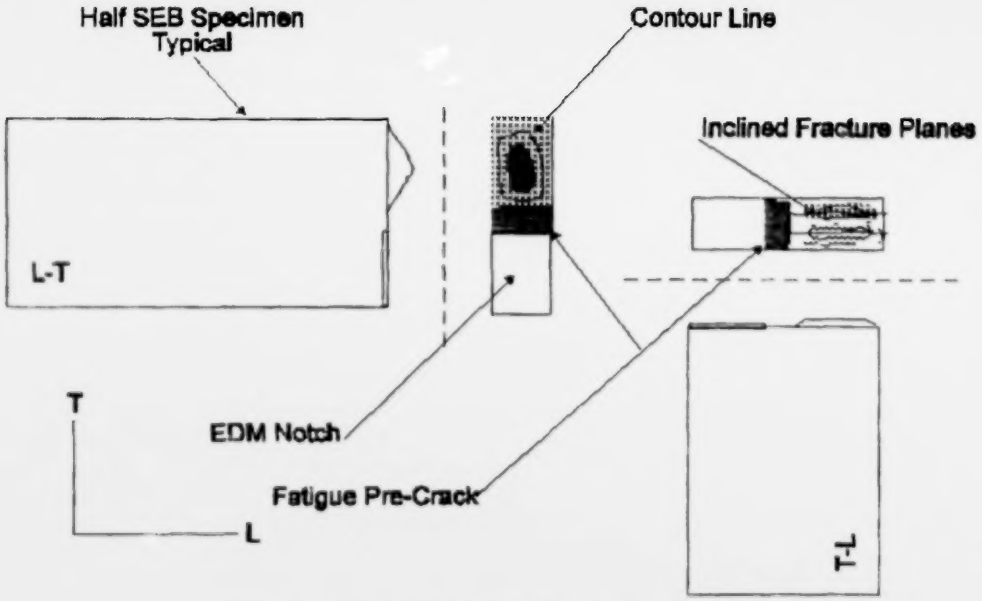

Figure 5 - X80 L-T And T-L Fracture Surface Appearance.

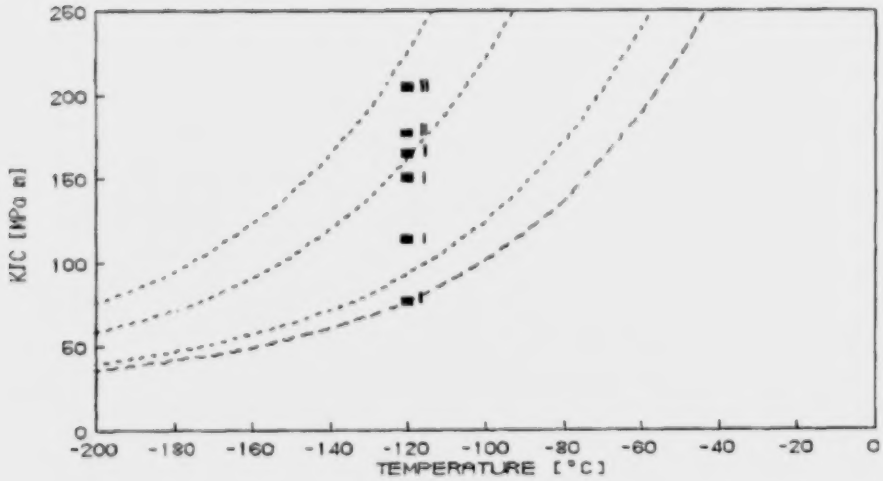

Figure 6 - X80-B L-T Master Curve. (Intermediate Loading At -120°C)

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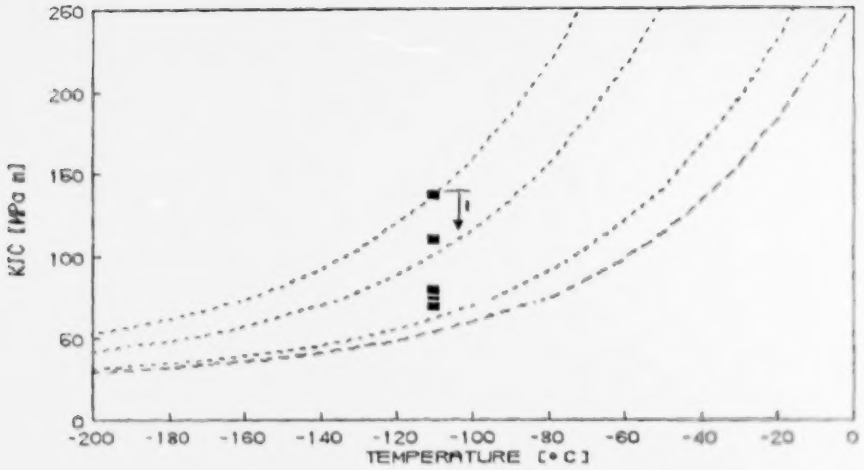

Figure 7 - X80-B T-L Master Curve.(Intermediate Loading at -110°C)

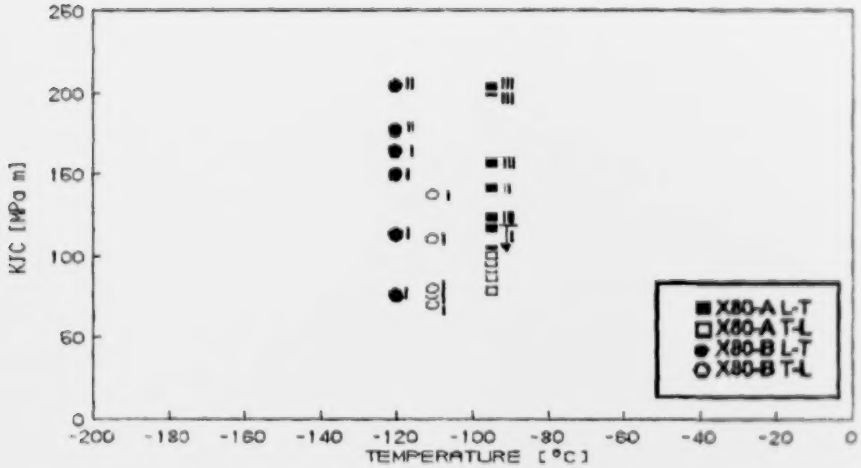

Figure 8 - Combined X80 L-T And T-L Results. (Intermediate Loading)

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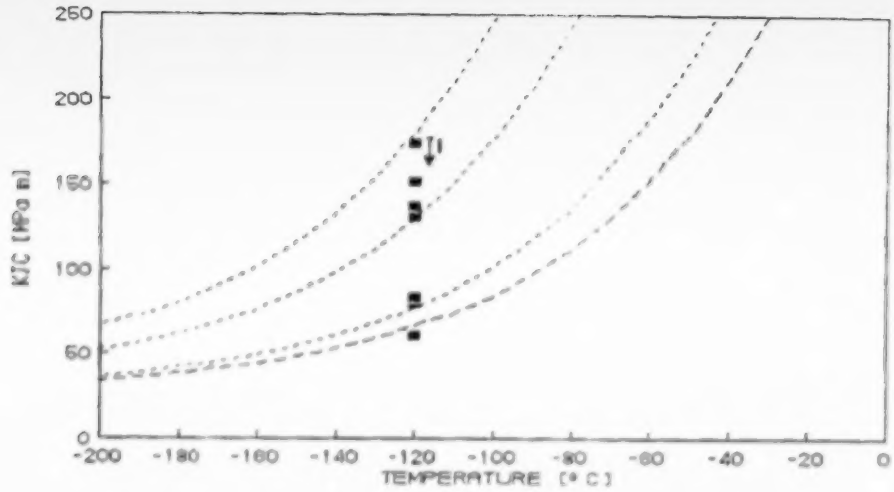

Figure 9 - A517 L-T Master Curve. (Intermediate Loading at -120°C)

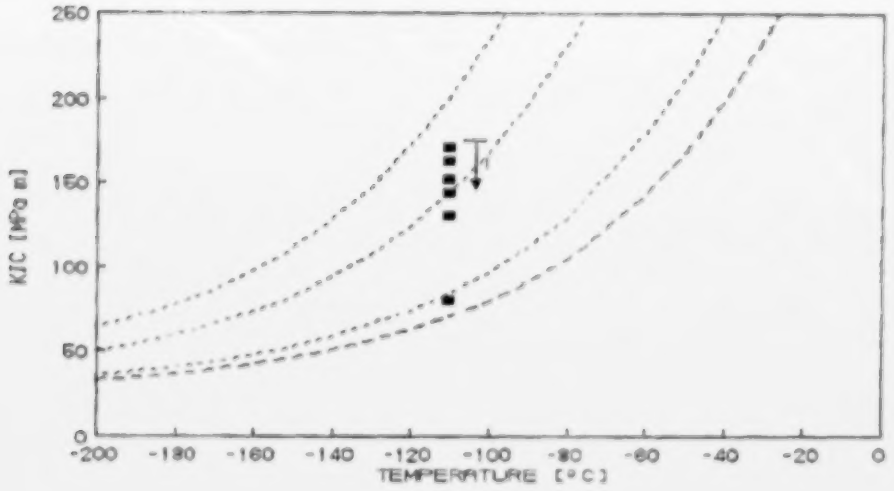

Figure 10 - A517 T-L Master Curve. (Intermediate Loading at -110°C)

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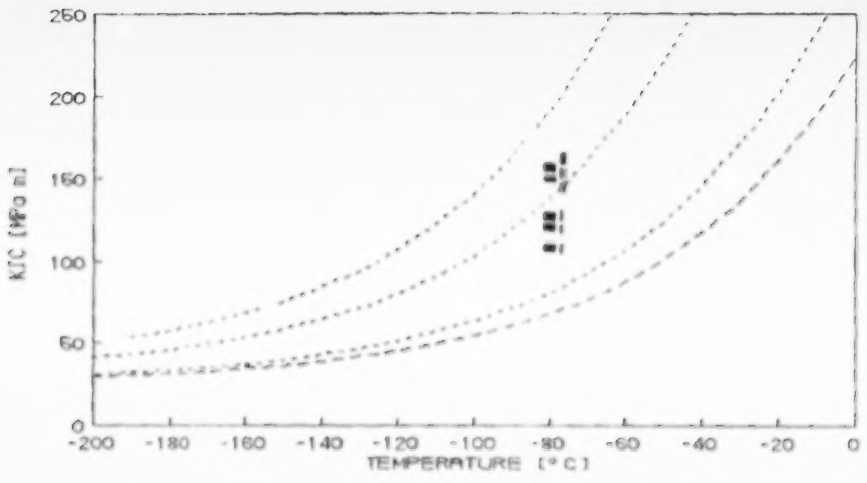

Figure 11 - A517 Weld Master Curve. (Quasi-Static Loading at -80°C)

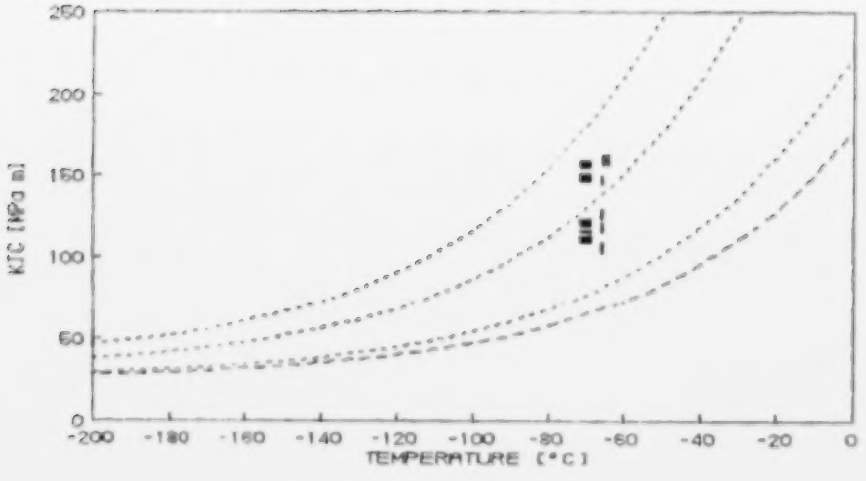

Figure 12 - A517 Weld Master Curve. (Intermediate Loading At -70°C)

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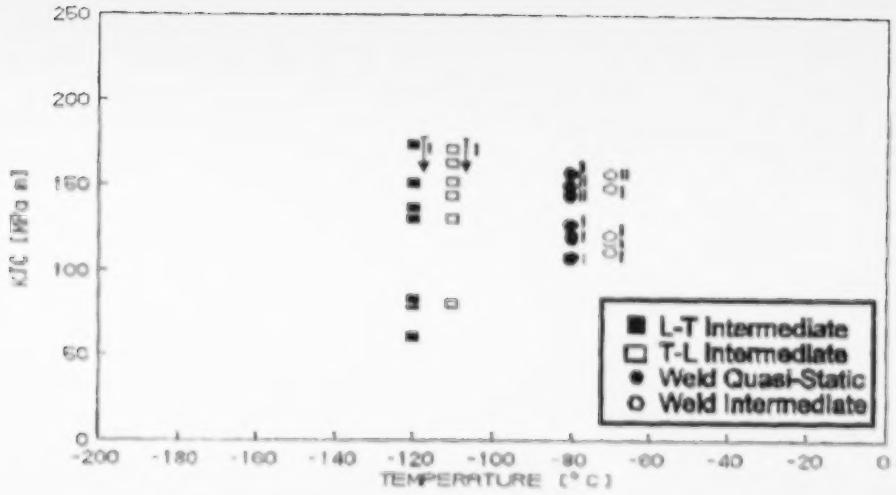

Figure 13 - Combined A517 Plate And Weld Results.

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wt %	ASTM A517	X80-A (IPSCO)	X80-B (BHP)
C	0.13	0.06	0.06
Mn	0.76	1.54	1.55
P	0.017	0.014	0.012
S	0.001	0.005	0.004
Si	0.31	0.15	0.15
Cu	0.40	0.41	0.01
Ni	0.86	0.28	0.01
Cr	0.46	0.19	0.05
Mo	0.43	0.30	0.24
V	-	0.04	-
Nb	-	0.08	0.08
Ti	-	0.03	0.021
Al	0.040	0.045	0.030
B	-	0.0013	0.005

Table 1 – Plate Chemical Composition

Material	Orientation	Loading Rate	Test Temperature °C
X80-A	L-T	Intermediate	-95
X80-A	T-L	Intermediate	-95
X80-B	L-T	Intermediate	-120
X80-B	T-L	Intermediate	-110
A517 Plate	L-T	Intermediate	-120
A517 Plate	T-L	Intermediate	-110
A517 Weld	-	Quasi-Static	-80
A517 Weld	-	Intermediate	-70

Table 2 – Original Fracture Test Matrix.

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Specimen ID	Rate	Temp. °C	0.2% PS MPa	UTS MPa	Elong. %
X80-A L(I1)	I	-95	628	893	23
X80-A T(I1)	I	-95	-	839	21
X80-A T(I2)	I	-95	644	939	20
X80-B L(I1)	I	-110	637	850	-
X80-B L(I2)	I	-110	653	885	26
X80-B T(I1)	I	-110	679	878	23
X80-B T(I2)	I	-110	735	887	27
A517P T(Q1)	Q/S	-100	851	953	24
A517P T(Q2)	Q/S	-100	N/A	934	20
A517P L(I1)	I	-110	735	1,053	22
A517P L(I2)	I	-110	715	982	18
A517P T(I1)	I	-110	700	949	20
A517P T(I2)	I	-110	N/A	986	23
A517W I1	I	-70	590*	908	21

Q – quasi-static I – Intermediate * Estimated.

Table 3 - Tensile Test Results.

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Type & Orient.	Rate	Temp. °C	0.2% PS MPa	b_0 mm	K_{Jc} Limit MPa√m
X80-A L-T	I	-95	628	16	260
X80-A T-L	I	-95	644	16	263
X80-B L-T	I	-110	645	16	264
X80-B T-L	I	-110	712	16	277
A517P L-T	I	-110	725	10	221
A517P T-L	I	-110	700	10	217
A517W	I	-70	590	10	199

E = 202 GPa

Table 4 - Specimen K_{Jc} Capacities.

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Specimen ID	Temp °C	Type	P_{max} kN	CMOD mm	a/W	K_{Jc} MPa√m	K_{Jc}(1T) MPa√m
X80-A-L1	-95	I	10.8	0.6	0.53	127	102
X80-A-L9	-95	I	14.0	0.6	0.50	147	118
X80-A-L11	-95	III	14.9	0.6	0.48	156	125
X80-A-L2	-95	II	13.7	0.8	0.50	179	142
X80-A-L7	-95	III	16.9	1.0	0.48	198	157
X80-A-L10	-95	II	14.6	0.9	0.50	199	158
X80-A-L6	-95	III	14.5	1.3	0.52	255	201
X80-A-L3	-95	III	15.4	1.6	0.51	265(260)	(205)
X80-A-L8	-95	III	15.5	1.8	0.48	294(260)	(205)
X80-A-L5	-95	IV	14.5	1.8	0.50	325(260)	(205)

( ) – censored

Table 5 –X80-A L-T Orientation - Intermediate Loading Rate.

Scale Parameter K_o = 199 MPa√m

Median K_{Jc} = 183 MPa√m

Reference Temperature T_o = -136 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 136)]$

Upper Tolerance Bound: K_{Jc} (95%) = 34.5 + 101.3 exp[0.019 (T + 136)]

Lower Tolerance Bound: K_{Jc} (5%) = 25.2 + 36.6 exp[0.019 (T + 136)]

Margin Adjusted Lower Bound Curve: K_{Jc} (LB) = 25.2 + 36.6 exp[0.019(T + 125)]

Table 6 – X80-A L-T Master Curve Analysis - Intermediate Loading Rate at -95°C.

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Specimen ID	Temp °C	Type	P_{max} kN	CMOD mm	a/W	K_{Jc} MPa√m	K_{Jc}(1T) MPa√m
X80-A-T2	-95	I	12.0	0.5	0.50	98	80
X80-A-T3	-95	I	13.1	0.4	0.48	108	88
X80-A-T4	-95	I	12.8	0.4	0.49	114	93
X80-A-T5	-95	I	11.3	0.4	0.51	119	96
X80-A-T6	-95	I	10.6	0.5	0.51	120	97
X80-A-T7	-95	I	13.6	0.5	0.49	125	101

Table 7 –X80-A T-L Orientation - Intermediate Loading Rate.

Scale Parameter K_o = 94 MPa√m

Median K_{Jc} = 88 MPa√m

Reference Temperature T_o = -85 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 85)]$

Upper Tolerance Bound: K_{Jc} (95%) = 34.5 + 101.3 exp[0.019 (T + 85)]

Lower Tolerance Bound: K_{Jc} (5%) = 25.2 + 36.6 exp[0.019 (T + 85)]

Margin Adjusted Lower Bound Curve: : K_{Jc} (LB) = 25.2 + 36.6 exp[0.019(T + 71)]

Table 8 – X80-A T-L Master Curve Analysis – Intermediate Loading Rate at -95°C.

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Specimen ID	Temp °C	Type	P_{max} kN	CMOD mm	a/W	K_{Jc} MPa√m	K_{Jc}(1T) MPa√m
X80-B-L4	-120	I	8.6	0.2	0.53	96	78
X80-B-L3	-120	I	12.0	0.3	0.52	144	115
X80-B-L1	-120	I	13.8	0.6	0.52	193	151
X80-B-L2	-120	I	13.6	0.6	0.48	212	166
X80-B-L6	-120	II	12.6	0.8	0.52	228	178
X80-B-L5	-120	II	13.0	1.0	0.50	285(264)	(206)

Table 9 –X80-B L-T Orientation - Intermediate Loading Rate.

Scale Parameter K_o = 174 MPa√m

Median K_{Jc} = 161 MPa√m

Reference Temperature T_o = -153 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 153)]$

Upper Tolerance Bound: K_{Jc} (95%) = 34.5 + 101.3 exp[0.019 (T + 153)]

Lower Tolerance Bound: K_{Jc} (5%) = 25.2 + 36.6 exp[0.019 (T + 153)]

Margin Adjusted Lower Bound Curve: : K_{Jc} (LB) = 25.2 + 36.6 exp[0.019(T + 139)]

Table 10 – X80-B L-T Master Curve Analysis – Intermediate Loading Rate at -120°C.

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Specimen ID	Temp °C	Type	P_{max} kN	CMOD mm	a/W	K_{Jc} MPa√m	K_{Jc}(1T) MPa√m
X80-B-T3	-110	I	10.0	0.4	0.51	86	70
X80-B-T8	-110	I	10.8	0.3	0.50	95	77
X80-B-T6	-110	I	11.0	0.2	0.48	100	81
X80-B-T7	-110	I	11.4	0.4	0.49	139	111
X80-B-T4	-110	I	10.9	0.4	0.49	140	111
X80-B-T1	-110	I	9.7	0.2	0.50	175	138

Table 11 –X80-B T-L Orientation - Intermediate Loading Rate.

Scale Parameter K_o = 109 MPa√m

Median K_{Jc} = 102 MPa√m

Reference Temperature T_o = -111 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 111)]$

Upper Tolerance Bound: K_{Jc} (95%) = $34.5 + 101.3 \exp[0.019 (T + 111)]$

Lower Tolerance Bound: K_{Jc} (5%) = $25.2 + 36.6 \exp[0.019 (T + 111)]$

Margin Adjusted Lower Bound Curve: : K_{Jc} (LB) = $25.2 + 36.6 \exp[0.019(T + 97)]$

Table 12 X80-B T-L Master Curve Analysis – Intermediate Loading Rate at -110°C.

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Specimen ID	Temp °C	Type	P_{max} kN	CMOD mm	a/W	K_{Jc} MPa√m	$K_{Jc}(1T)$ MPa√m
A517P-1	-80	II	11.0	0.8	0.51	399	308
A517P-2	-90	III	11.5	0.7	0.51	305	235
A517P-3	-100	IV	11.1	0.4	0.51	230	177
A517P-4	-110	IV	11.3	0.8	0.51	368	283
A517P-6	-120	II	11.1	0.6	0.52	272	209

Table 13 – A517 Plate T-L Orientation - Quasi-Static Loading Rate.

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Specimen ID	Temp °C	Type	P_{max} kN	CMOD mm	a/W	K_{Jc} MPa√m	K_{Jc} (1T) Mpa√m
A517P-L15	-120	I	4.2	0.1	0.50	73	61
A517P-L10	-120	I	5.8	0.2	0.50	99	81
A517P-L11	-120	I	6.3	0.2	0.50	104	85
A517P-L9	-120	I	9.5	0.3	0.51	166	132
A517P-L8	-120	I	9.0	0.3	0.53	173	138
A517P-L5	-120	I	10.6	0.3	0.51	191	152
A517P-L19	-120	I	11.6	0.4	0.51	229(221)	(175)
A517P-L7*	-120	I	8.0	0.2	0.51	139	112
A517P-L12*	-120	I	8.9	0.2	0.49	148	119
A517P-L18*	-120	I	8.0	0.2	0.50	150	120
A517P-L16*	-120	I	7.8	0.3	0.53	151	121
A517P-L6*	-120	I	11.1	0.3	0.47	188	149
A517P-L17*	-120	I	10.5	0.4	0.52	212	168
A517P-L13*	-120	I	12.0	0.4	0.50	231(221)	(175)

* - crack front straightness limit exceeded

Table 14 – A517 Plate L-T Orientation - Intermediate Loading Rate.

Scale Parameter K_o = 142 MPa√m

Median K_{Jc} = 131 MPa√m

Reference Temperature T_o = -139 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 139)]$

Upper Tolerance Bound: $K_{Jc}(95\%) = 34.5 + 101.3 \exp[0.019 (T + 139)]$

Lower Tolerance Bound: $K_{Jc}(5\%) = 25.2 + 36.6 \exp[0.019 (T + 139)]$

Margin Adjusted Lower Bound Curve: : $K_{Jc}(LB) = 25.2 + 36.6 \exp[0.019(T + 126)]$

Table 15 – A517 Plate L-T Master Curve Analysis – Intermediate Loading Rate at -120°C

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Specimen ID	Temp °C	Type	P_{max} kN	CMOD mm	a/W	K_{Jc} MPa√m	K_{Jc} (1T) MPa√m
A517P-T14	-110	I	5.9	0.1	0.51	101	82
A517P-T12	-110	I	9.4	0.2	0.51	166	132
A517P-T13	-110	I	10.1	0.3	0.51	182	145
A517P-T8	-110	I	10.1	0.3	0.51	192	153
A517P-T9	-110	I	10.9	0.3	0.51	207	164
A517P-T11	-110	I	12.4	0.5	0.51	265(217)	(172)

Table 16 – A517 Plate T-L Orientation - Intermediate Loading Rate.

Scale Parameter K_o = 158 MPa√m

Median K_{Jc} = 146 MPa√m

Reference Temperature T_o = -136 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 136)]$

Upper Tolerance Bound: K_{Jc} (95%) = 34.5 + 101.3 exp[0.019 (T + 136)]

Lower Tolerance Bound: K_{Jc} (5%) = 25.2 + 36.6 exp[0.019 (T + 136)]

Margin Adjusted Lower Bound Curve: : K_{Jc} (LB) = 25.2 + 36.6 exp[0.019(T + 122)]

Table 17 – A517 Plate T-L Master Curve Analysis – Intermediate Loading Rate at -110°C.

Specimen ID	Temp °C	Type	P_{max} kN	LLD mm	a/W	K_{Jc} MPa√m	K_{Jc} (1T) MPa√m

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A517W-16	-80	I	7.2	0.3	0.51	137	110
A517W-8	-80	I	8.0	0.3	0.50	152	122
A517W-18	-80	I	8.5	0.3	0.49	160	128
A517W-11	-80	II	8.6	0.5	0.51	190	151
A517W-14	-80	II	9.2	0.4	0.50	197	156
A517W-12	-80	II	9.3	0.6	0.50	235(199)	(158)
A517W-13*	-80	I	8.7	0.4	0.50	82	145
A517W-17*	-80	II	9.1	0.5	0.49	200	159

* - crack front straightness limit exceeded

Table 18 – A517 Weld - Quasi-Static Loading Rate.

Scale Parameter K_o = 149 MPa$\sqrt{m}$

Median K_{Jc} = 138 MPa$\sqrt{m}$

Reference Temperature T_o = -103 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 103)]$

Upper Tolerance Bound: K_{Jc} (95%) = 34.5 + 101.3 exp[0.019 (T + 103)]

Lower Tolerance Bound: K_{Jc} (5%) = 25.2 + 36.6 exp[0.019 (T + 103)]

Margin Adjusted Lower Bound Curve: : K_{Jc} (LB) = 25.2 + 36.6 exp[0.019(T + 89)]

Table 19 – A517 Weld Master Curve Analysis – Quasi-Static Loading Rate at -80°C.

Specimen ID	**Temp °C**	**Type**	**P_{max} kN**	**CMOD mm**	**a/W**	**K_{Jc} MPa$\sqrt{m}$**	**K_{Jc} (1T) MPa$\sqrt{m}$**
A517W-35	-70	I	7.8	0.2	0.50	139	112
A517W-24	-70	I	8.1	0.3	0.50	147	118
A517W-27	-70	I	8.2	0.3	0.50	148	119

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A517W-22	-70	I	8.2	0.3	0.50	153	122
A517W-21	-70	I	7.9	0.5	0.48	188	150
A517W-36	-70	II	9.7	0.4	0.50	202(199)	158
A517W-32*	-70	I	7.8	0.4	0.54	176	140
A517-W19*	-70	I	9.3	0.4	0.49	185	147

*crack front straightness limit exceeded.

Table 20 – A517 Weld - Intermediate Loading Rate.

Scale Parameter K_o = 141 MPa$\sqrt{m}$

Median K_{Jc} = 130 MPa$\sqrt{m}$

Reference Temperature T_o = -89 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 89)]$

Upper Tolerance Bound: K_{Jc} (95%) = 34.5 + 101.3 exp[0.019 (T + 89)]

Lower Tolerance Bound: K_{Jc} (5%) = 25.2 + 36.6 exp[0.019 (T + 89)]

Margin Adjusted Lower Bound Curve: : K_{Jc} (LB) = 25.2 + 36.6 exp[0.019(T + 75)]

Table 21 –A517 Weld Master Curve Analysis - Intermediate Loading Rate at -70°C

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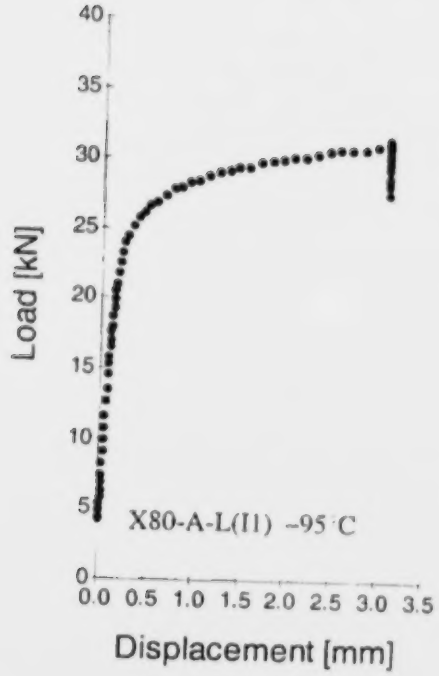
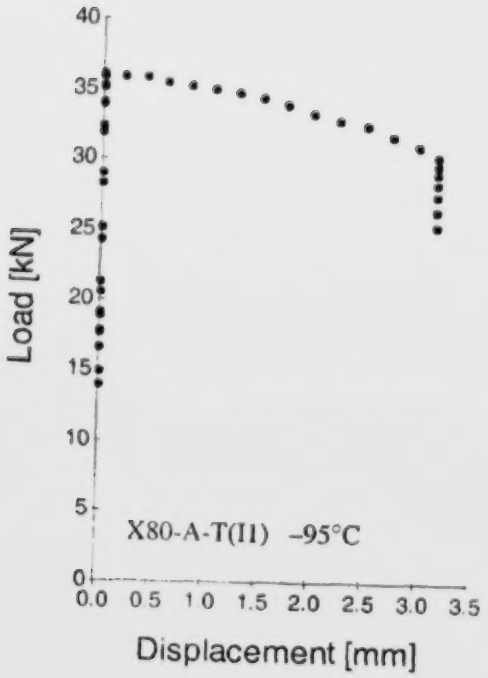
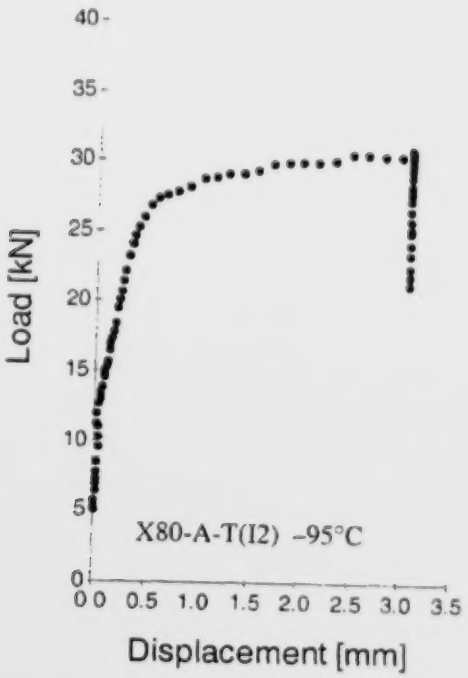
Appendix A

Tensile Test Load-Displacement Curves.


Load [kN]
Displacement [mm]
X80-A-L(I1) –95°C
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
0 5 10 15 20 25 30 35 40


Load [kN]
Displacement [mm]
X80-A-T(I1) –95°C
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
0 5 10 15 20 25 30 35 40


Load [kN]
Displacement [mm]
X80-A-T(I2) –95°C
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
0 5 10 15 20 25 30 35 40

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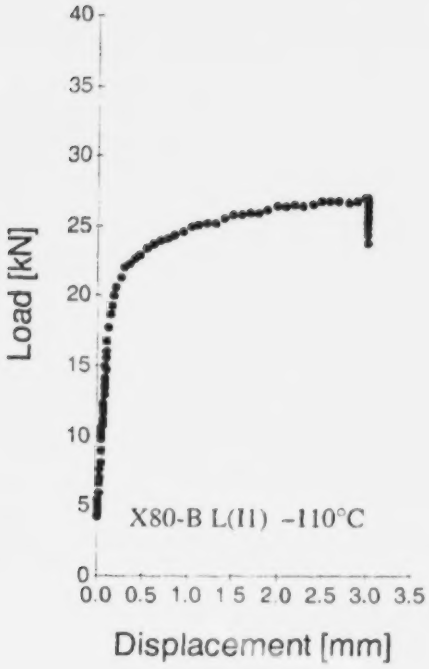

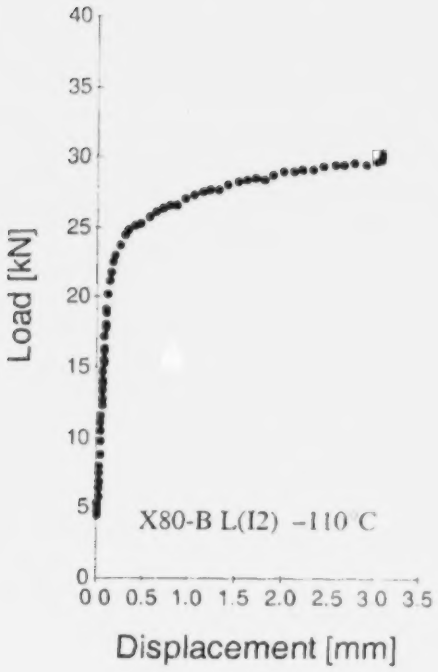

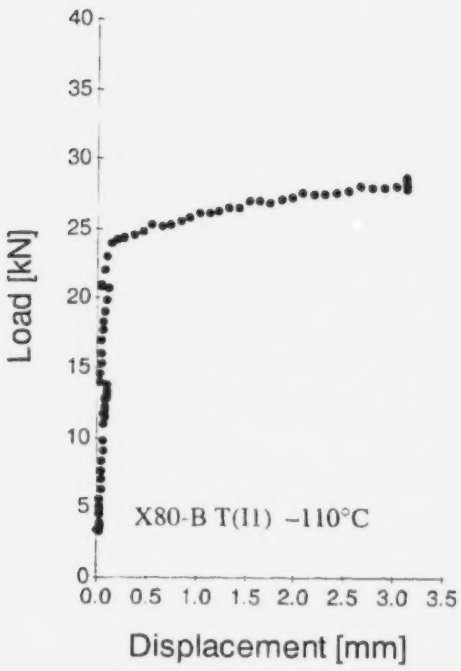

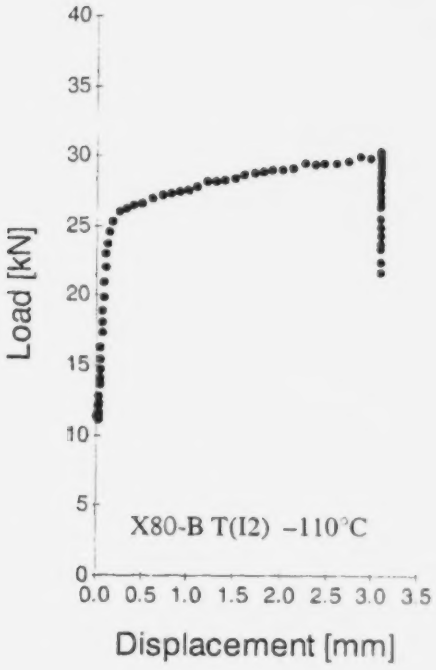

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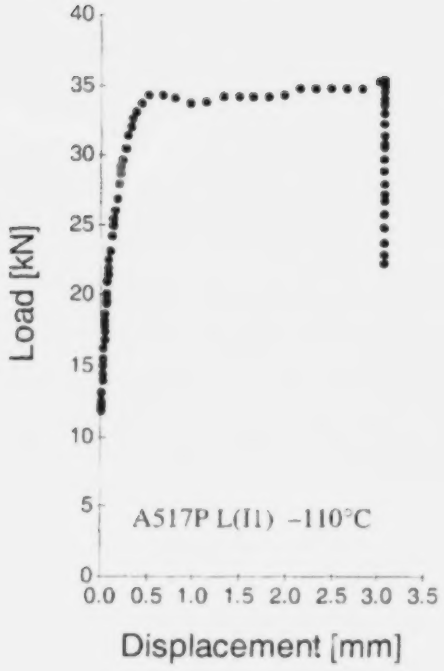

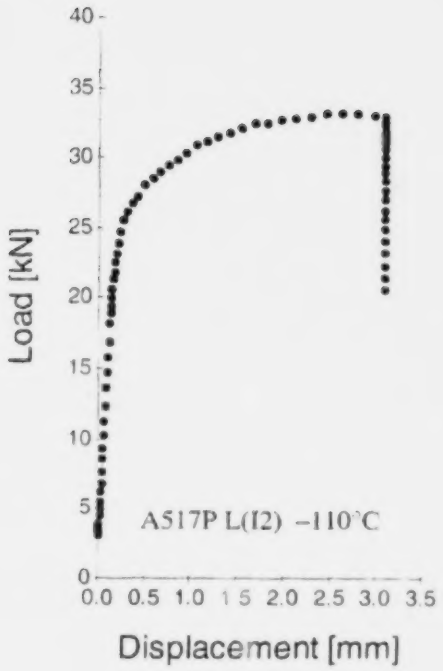

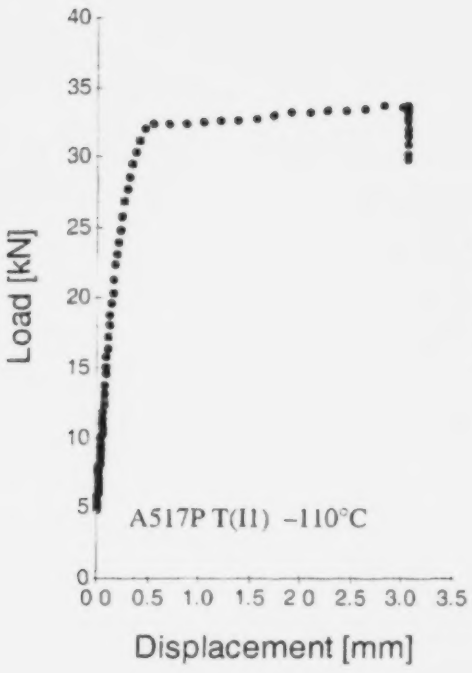

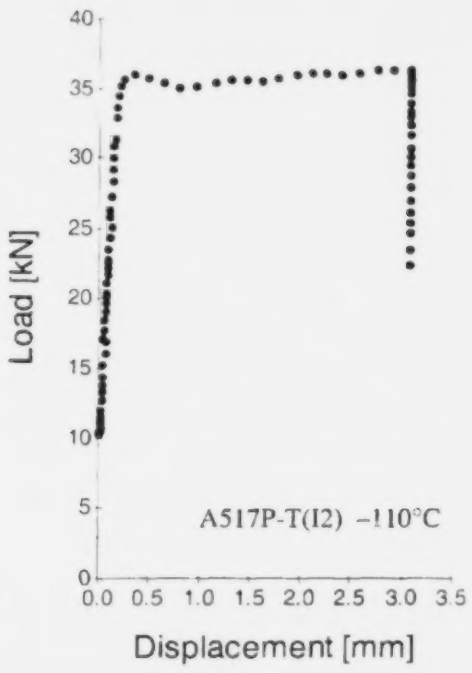

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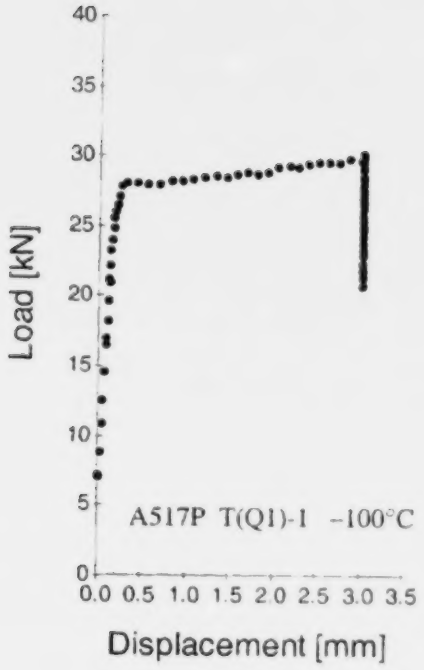

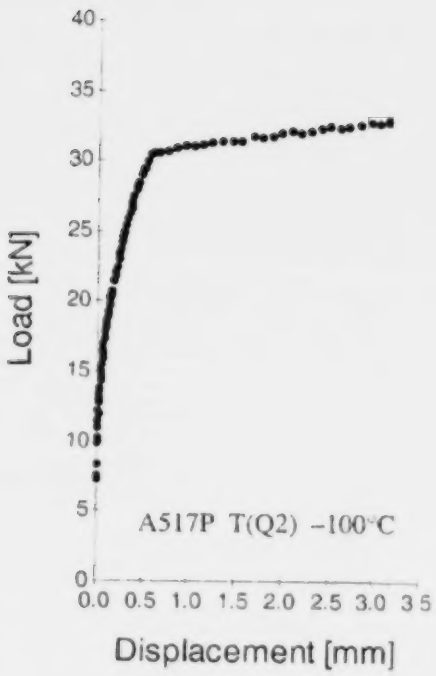

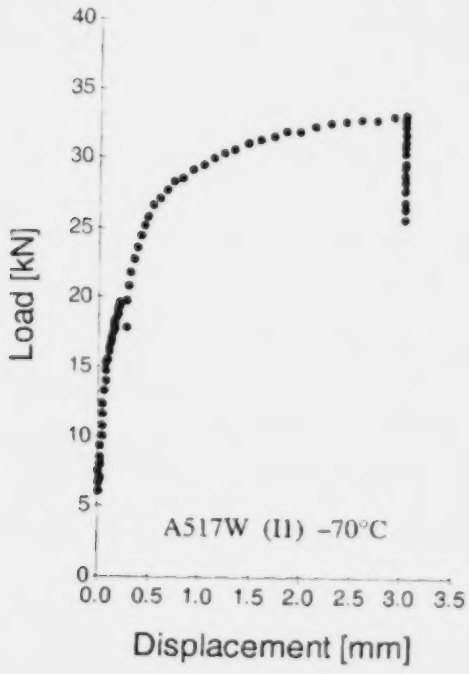

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Appendix B

Specimen Dimensions, Crack Sizes, and Toughness Measurements

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S/N	T	W	B	B_N	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	ave	°C
						mm									
L1	-95	29.50	9.14	7.10	15.65	15.64	15.50	15.40	15.76	15.92	16.00	16.00	16.00	15.76	
L2	-95	29.52	9.09	7.03	14.78	14.76	14.52	14.29	14.72	14.85	14.90	14.86	14.88	14.72	
L3	-95	29.50	9.06	7.13	15.21	15.24	15.22	15.15	14.91	14.56	14.82	14.94	14.99	14.99	
L5	-95	29.50	9.09	6.95	14.79	14.80	14.81	14.81	14.67	14.16	14.34	14.67	14.78	14.63	
L6	-95	29.54	9.09	6.96	15.19	15.09	15.02	15.22	15.50	15.50	15.49	15.45	15.38	15.32	
L7	-95	29.52	9.20	7.13	14.26	14.19	13.92	13.56	14.07	14.43	14.52	14.56	14.55	14.21	
L8	-95	29.52	9.11	7.03	14.34	14.26	14.11	13.99	14.08	14.55	14.52	14.51	14.50	14.30	
L9	-95	29.54	9.15	7.10	14.74	14.77	14.79	14.81	14.56	14.34	14.61	14.81	14.88	14.69	
L10	-95	29.50	9.08	7.04	14.81	14.89	14.92	14.97	14.96	14.77	14.59	14.69	14.74	14.82	
L11	95	29.50	9.10	7.06	14.45	14.36	14.03	13.57	14.07	14.31	14.41	14.46	14.52	14.21	

Table B1 – X80-A Specimen Dimensions and Crack Sizes (L-T Intermediate).

S/N	T °C	a/W	P_m kN	t_f s	K_e MPa√m	J_e	J_p kJ/m²	J_c	K_{Jc} MPa√m	K_{Jc}/s MPa√m/s
L1	-95	0.53	10.8	0.18	95.8	42.0	33.0	75.0	126.7	703
L2	-95	0.50	13.8	0.26	108.1	54.6	95.5	150.0	179.2	689
L3	-95	0.51	15.4	0.42	124.1	71.9	256.4	328.3	265.0	631
L5	-95	0.50	14.5	0.44	113.7	60.4	433.3	494.7	325.0	738
L6	-95	0.52	14.5	0.42	121.9	69.5	234.4	303.9	255.0	607
L7	-95	0.48	16.9	0.35	124.0	71.9	111.2	183.1	197.9	566
L8	-95	0.48	15.5	0.43	116.2	63.1	341.7	404.9	294.3	684
L9	-95	0.50	14.0	0.25	108.0	54.7	46.4	101.1	147.1	588
L10	-95	0.50	14.6	0.30	116.2	63.1	122.1	185.2	199.1	663
L11	-95	0.48	14.9	0.26	111.0	57.5	56.3	113.9	156.1	600

Table B2 –X80-A Fracture Toughness Results (L-T Intermediate).

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S/N	T	W	B	B_N	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	ave	°C
						mm									
T2	-95	29 86	9.15	7.39	14 71	14 79	14.79	14 64	14.57	14 60	14 95	15 08	15.18	14 79	
T3	-95	29 76	9.18	7.37	14 15	14.16	14.19	14 19	14.23	14 28	14 38	14 54	14 56	14 29	
T4	-95	29 82	9 15	7 10	14.70	14 66	14 61	14.57	14 62	14 65	14 74	14 84	14 93	14 69	
T5	-95	29 86	9.18	7 34	15.30	15 34	15.28	15 21	15 20	15 20	15 17	15.16	15.09	15.22	
T6	-95	29 82	9 16	7.08	15.18	15.17	15 09	15.08	15.10	15.11	15.12	15.13	15.11	15 12	
T7	-95	29 74	9 14	7 31	14.43	14.56	14.49	14.40	14 39	14 33	14 35	14 37	14.42	14 41	

Table B3 – X80-A Specimen Dimensions and Crack Sizes (T-L Intermediate).

S/N	T °C	a/W	P_m kN	t_f s	K_e MPa√m	J_e	J_p kJ/m²	J_c	K_{Jc} MPa√m	K_{Jc}/s MPa√m/s
T2	-95	0.50	12 0	0 22	89.4	37 4	7 7	45.1	98 2	446
T3	-95	0.48	13.1	0.29	93.2	40.6	14.0	54.6	108.1	372
T4	-95	0.49	12.8	0.16	96.3	43 3	17.9	61.2	114.4	713
T5	-95	0 51	11.3	0 20	87.5	35 8	29.9	65.7	118.6	595
T6	-95	0.51	10 6	0.15	83 3	32.3	35.1	67.5	120 1	800
T7	-95	0 49	13.6	0.17	99.0	45 8	27.0	72.8	124.8	735

Table B4 –X80-A Fracture Toughness Results (T-L Intermediate).

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S/N	T	W	B	B_N	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	ave	°C
						mm									
L1	-120	29.96	8.60	6.49	15.33	15.70	15.75	15.80	15.74	15.54	15.20	15.11	15.07	15.49	
L2	-120	29.96	8.51	6.03	14.51	14.40	14.41	14.52	14.63	14.66	14.58	14.41	14.12	14.49	
L3	-120	29.98	8.55	6.20	15.36	15.40	15.57	15.64	15.71	15.74	15.74	15.62	15.38	15.59	
L4	-120	29.98	8.50	6.85	15.96	15.99	16.06	16.13	16.17	16.14	15.99	15.71	15.47	15.99	
L5	-120	30.02	8.51	6.34	14.90	15.09	15.23	15.27	15.21	15.10	14.99	14.84	14.77	15.07	
L6	-120	29.96	8.49	6.45	15.01	15.50	15.74	15.77	15.76	15.68	15.56	15.55	15.60	15.61	

Table B5 – X80-B Specimen Dimensions and Crack Sizes (L-T Intermediate).

S/N	T	a/W	P_m	t_f	K_e	J_e	J_p	J_c	K_{Jc}	K_K/s
	°C		kN	s	MPa√m		kJ/m²		MPa√m	MPa√m/s
L1	-120	0.52	13.8	0.36	120.1	67.5	105.8	173.3	192.5	536
L2	-120	0.48	13.6	0.29	111.1	57.7	151.6	209.3	211.6	731
L3	-120	0.52	12.0	0.23	107.8	54.4	42.8	97.1	144.2	626
L4	-120	0.53	8.6	0.15	78.6	28.8	14.4	43.3	96.2	640
L5	-120	0.50	13.0	0.37	109.3	55.8	324.2	380.1	285.2	770
L6	-120	0.52	12.6	0.40	112.0	58.6	184.9	243.5	228.3	570

Table B6 –X80-B Fracture Toughness Results (L-T Intermediate).

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S/N	T	W	B	B_N	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	ave	°C
						mm									
T1	-110	29.97	8.85	6.20	14.55	14.58	14.67	14.81	14.87	14.91	15.11	15.17	15.21	14.87	
T3	-110	30.02	8.53	6.43	15.00	15.06	15.31	15.37	15.42	15.46	15.49	15.48	15.40	15.35	
T4	-110	29.96	8.50	6.00	14.43	14.47	14.52	14.61	14.64	14.70	14.76	14.87	14.90	14.65	
T6	-110	29.96	8.63	6.46	14.55	14.57	14.49	14.50	14.51	14.49	14.51	14.46	14.40	14.50	
T7	-110	29.96	8.49	6.39	13.60	14.08	14.40	14.73	14.88	15.01	15.01	15.04	15.10	14.59	
T8	-110	29.98	8.46	6.36	14.64	14.76	14.89	14.96	14.95	14.95	14.98	15.01	14.98	14.91	

Table B7 – X80-B Specimen Dimensions and Crack Sizes (T-L Intermediate).

S/N	T °C	a/W	P_m kN	t_f s	K_e MPa√m	J_e	J_p kJ/m²	J_c	K_{Jc} MPa√m	K_{Jc}/s MPa√m/s
T1	-110	0.50	9.7	0.21	81.8	31.3	112.5	143.8	175.4	833
T3	-110	0.51	10.0	0.15	85.7	34.3	-	34.3	85.7	571
T4	-110	0.49	10.9	0.20	90.9	38.6	52.6	91.2	139.7	700
T6	-110	0.48	11.0	0.18	86.5	35.0	12.2	47.2	100.5	561
T7	-110	0.49	11.4	0.15	92.8	40.3	50.2	90.5	139.1	926
T8	-110	0.50	10.8	0.14	89.5	37.5	4.9	42.4	95.2	680

Table B8 –X80-B Fracture Toughness Results (T-L Intermediate).

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S/N	T	W	B	BN	a1	a2	a3	a4	a5	a6	a7	a8	a9	avg
L1	-110	18.0	8.96	7.26	8.55	8.48	8.34	8.42	8.61	8.68	8.67	8.60	8.43	8.54
L4	-110	17.9	8.94	7.09	8.51	8.27	7.92	8.05	8.33	8.72	8.90	8.94	8.89	8.48
L5	-120	17.9	8.94	7.13	9.48	9.46	9.37	9.26	8.93	8.63	8.58	8.95	9.20	9.06
L6	-120	18.0	8.98	7.28	9.61	9.58	9.38	9.14	8.63	8.18	8.13	8.64	8.91	8.87
L7	-120	17.9	8.97	6.99	9.68	9.68	9.59	9.31	8.80	8.47	8.44	9.03	9.27	9.10
L8	-120	17 9	9 02	6.93	9.38	9.55	9.63	9.64	9.62	9.55	9.42	9 27	9.15	9.50
L9	-120	17.9	8.95	7.06	9.10	9.22	9.24	9.20	8.98	8.78	8.76	9.00	9.16	9.04
L10	-120	17.9	8.97	6.91	9.39	9.22	8.65	8.57	8.85	9.24	9.30	9.06	8.74	9.00
L11	-120	17.9	8.99	6.98	9.00	8.83	8.64	8.66	8.82	8.98	9.06	9.02	8.94	8.87
L12	-120	17.9	8.96	7.05	8.76	8.57	8.13	8.24	8.60	9.06	9 24	9.34	9.34	8.79
L13	-120	17.9	8.96	6.72	9.18	8 95	8.48	8.56	8.88	9.27	9.51	9.64	9.66	9.09
L15	-120	17.9	8.91	7.03	9.04	8 99	8.70	8.66	8.92	9.17	9 23	9.22	9.16	9 00
L16	-120	17.9	8.98	6.82	9.59	9.43	9.06	9.07	9.43	9.80	9.97	9.11	10.15	9 59
L17	-120	18.0	8.93	6.64	9.13	8.79	8.61	8.81	9.27	9.69	9.83	9.99	10.09	9.32
L18	-120	17.9	8.95	6.91	8.97	8.72	8.40	8.51	8.81	9.14	9.31	9.46	9.48	8.95
L19	-120	17.9	8.94	6.86	9.23	9.06	8.78	8.84	9.08	9.35	9.49	9.53	9.49	9.19

Table B9 – A517 Plate Specimen Dimensions and Crack Sizes (L-T Intermediate).

S/N	T °C	a/W	P_m kN	t_f s	K_e MPa√m	J_e	J_p kJ/m²	J_c	K_{Jc} MPa√m	K_{Jc}/s MPa√m/s
L1	-120	0.47	12.5	0.22	189.2	167.4	34.5	201.8	207 8	945
L4	-120	0.47	12.9	0.24	198.9	184 8	71 6	256.4	234 2	975
L5	-120	0.51	10.6	0 25	179.6	150.8	20.0	170 8	191.2	764
L6	-120	0 47	11.1	0 19	179.2	150.2	15.9	166.1	188.5	992
L7	-120	0 51	8.0	0 17	138.7	89.9	0.2	90.1	138 9	817
L8	-120	0.53	9.0	0.17	168.5	132.7	7.2	139.9	173.0	1,018
L9	-120	0.51	9.5	0.17	161.2	121.6	7 0	128.6	165 8	975
L10	-120	0.50	5.8	0.09	98.7	45.5	0.4	45.9	98.7	1,097
L11	-120	0 50	6 3	0.10	104 4	51.0	0 0	51.0	104.4	1,044
L12	-120	0 49	8.9	0 14	144.4	97.5	4.6	102.1	147.8	1,056
L13	-120	0 51	11.9	0.21	209.4	204.9	43.6	248.5	230.6	1,098
L15	-120	0.50	4.2	0 08	70.6	23.3	1 7	25.0	73.2	915
L16	-120	0.53	7.8	0.18	147.5	101 7	4.8	106.5	150.9	838
L17	-120	0 52	10 5	0 19	193.5	175.0	34.2	209.2	211.6	1,114
L18	-120	0 50	7.9	0 15	134.6	84.7	20.4	105.1	150.0	1,000
L19	-120	0 51	11.6	0 24	204 6	195.7	49.9	245 6	229.3	955

Table B10 –A517 Plate Fracture Toughness Results (T-L Intermediate).

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S/N	T	W	B	B_N	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	ave
°C						mm								
T1	-80	18 0	9 01	6.98	8 84	9 04	9 24	9 32	9.32	9 30	9 25	9 20	9.13	9.20
T2	-90	17 9	8.93	7.06	8 13	9 27	9 28	9 20	8.90	8.72	8 80	9.17	9 21	9.07
T3	-100	17 9	8.96	6.70	9 35	9.43	9 45	9.33	9.25	9 06	8 85	8.58	8.49	9.11
T4	-110	17.9	8.98	6.73	8.81	8.95	9 13	9.25	9.30	9 31	9.31	9 28	9.19	9 19
T6	-120	17 9	8.98	6 74	9 22	9 37	9 44	9 46	9.50	9.39	9 31	9 21	9 21	9 36

Table B11 – A517 Plate Specimen Dimensions and Crack Sizes (T-L Quasi-Static).

S/N	T	a/W	P_m	t_f	K_e	J_e	J_p	J_c	K_{Jc}	K_{Jc}/s
	°C		kN	s	MPa√m		kJ/m²		MPa√m	MPa√m/s
T1	-80	0.51	11 0	21 9	190.9	170.3	571.9	742.2	398.5	18.2
T2	-90	0 51	11.5	51.0	197 2	181.7	251.8	433.5	304 6	6.0
T3	-100	0 51	11.1	27.8	196.7	180.9	67.3	248 2	230.5	8 3
T4	-110	0 51	11.3	34 3	202 1	190.9	443.3	634 2	368.4	10 7
T6	-120	0.52	11.1	20.5	204.1	194 7	152.3	347.0	272.5	13.3

Table B12 – A517 Plate Fracture Toughness Results (T-L Quasi-Static).

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S/N	T	W	B	B_N	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	ave	°C
						mm									
T7	-90	17.9	8.95	6.74	8.81	9 01	9.13	9.20	9.22	9.24	9 21	9 16	9 06	9.14	
T8	-110	18.0	8 96	6.63	9 04	9.10	9.114	9 18	9.19	9.17	9.10	8.99	8 77	9.10	
T9	-110	17 9	9.02	6 96	8 94	9.09	9.17	9.21	9 224	9.23	9 17	9.06	8 91	9.14	
T11	-110	18.0	9.02	6 78	8 99	9.04	9 10	9.17	9.21	9.23	9 15	9.10	8.82	9.11	
T12	-110	17.9	8 99	6.85	8 77	8.90	9.02	9 11	9.16	9 17	9 13	9.04	8.95	9 05	
T13	-110	17.9	8.98	6.92	8 66	8.85	8.99	9.09	9.14	9 15	9 12	9 13	9.14	9.05	
T14	-110	17.9	9.04	6.95	8.80	8.93	9.07	9.18	9.21	9.18	9 11	8.98	8.77	9.06	

Table B13 – A517 Plate Specimen Dimensions and Crack Sizes (T-L Intermediate).

S/N	T	a/W	P_m	t_f	K_e	J_e	J_p	J_c	K_{Jc}	K_{Jc}/s
	°C		kN	s	MPa√m		kJ/m²		MPa√m	MPa√m/s
T7	-90	0.51	12.0	0.27	212.6	211 3	180.4	391.7	289 5	1,072
T8	-110	0 51	10.1	0.17	179.1	149.9	22.5	172.4	192.0	1,129
T9	-110	0.51	10.9	0.31	189.2	167 2	33 7	200 9	207.3	669
T11	-110	0.51	12.4	0 29	215.3	216.7	112 0	328.7	265 2	914
T12	-110	0 51	10.7	0 19	226.7	140.4	14 3	154.7	181 9	957
T13	-110	0.51	9.4	0.13	162.5	123.4	5.8	129.2	166.3	1,279
T14	-110	0.51	5.9	0.08	100.7	47 4	0.5	47.9	101.2	1,265

Table B14 – A517 Plate Fracture Toughness Results (T-L Intermediate).

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S/N	T	W	B	B_N	a_1	a_2 mm	a_3	a_4	a_5	a_6	a_7	a_8	a_9	ave	°C
W08	-80	18 0	8.91	7 07	9 37	9.43	9 36	9.21	8.91	8 64	8 65	8 92	9 07	9.02	
W11	-80	18.0	8.95	6.66	9.27	9 35	9.32	9 27	9.10	8 97	8.96	9 20	9 25	9.18	
W12	-80	18.0	8.96	6.75	9 10	9 19	9.21	9.16	9.01	8 86	8 80	8 97	9 15	9 04	
W13	-80	18 0	8.95	6.65	9 45	9 48	9.35	9 16	8 82	8 54	8 43	8 66	8 94	8.96	
W14	-80	18.0	8.89	6.75	8.98	8 80	8.59	8.63	8.90	9.19	9 37	9.44	9.39	9.01	
W16	-80	18.0	8 97	6.94	9 30	9.35	9.32	9.23	9.03	8 84	8.81	9 08	9.17	9.11	
W17	-80	17.9	8.99	6.87	9 37	9 32	9.16	8.94	8 62	8 29	8 32	8 78	9 12	8.83	
W18	-80	17 9	8.97	6.84	9.10	9 15	9 10	8.99	8 89	8.59	8.57	8.73	8.85	8 86	

Table B15 – A517 Weld Specimen Dimensions and Crack Sizes (Quasi-Static).

S/N	T °C	a/W	P_m kN	t_f s	K_e MPa√m	J_e	J_p kJ/m²	J_c	K_{Jc} MPa√m	K_{Jc}/s MPa√m/s
W08	-80	0 50	8.0	20.3	134 6	84.7	22.6	107.3	151.5	7.5
W11	-80	0.51	8 6	28 8	152.4	108.6	60 2	168.8	190.0	6.6
W12	-80	0 50	9.3	31 1	160.0	119.7	138 3	258.0	234 9	7 6
W13	-80	0.50	8.7	26.1	149 8	105 0	49 9	154 9	182.0	7 0
W14	-80	0 51	9.2	13 7	158 9	118 0	62.5	180.5	196.5	14.3
W16	-80	0 51	7.2	24.4	124 1	72.0	15 7	87.7	137.0	5 6
W17	-80	0 49	9.1	28.6	151.7	107.5	80.1	187.6	200.4	7.0
W18	-80	0.49	8 5	23 6	140.8	92.6	27.0	119 6	160.0	6.8

Table B16 – A517 Weld Fracture Toughness Results (Quasi-Static).

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S/N	T	W	B	B_N	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	ave	°C
						mm									
W19	-70	17.96	8.94	6.67	9.67	9.57	9.42	9.14	8.69	8.26	8.17	8.49	8.78	8.87	
W21	-70	17.97	8.96	6.60	8.67	8.74	8.78	8.76	8.71	8.64	9.59	8.63	8.64	8.69	
W22	-70	17.94	8.96	6.98	8.81	8.94	8.99	8.99	8.91	8.86	8.83	9.00	9.01	8.93	
W24	-70	17.96	8.99	7.09	8.90	9.00	9.05	9.06	8.97	8.87	8.82	8.98	9.01	8.96	
W27	-70	17.96	9.00	6.99	8.91	9.06	9.07	8.97	8.82	8.70	8.75	8.99	9.15	8.92	
W32	-70	17.94	8.98	6.89	9.29	9.15	8.92	9.11	9.58	10.02	10.30	10.46	10.63	9.65	
W35	-70	17.94	8.97	6.82	9.02	9.12	9.13	9.09	8.94	8.75	8.66	8.77	8.91	8.93	
W36	-70	17.96	8.97	7.22	8.99	8.87	8.66	8.76	8.99	9.14	9.19	9.20	9.08	8.98	

Table B17 – A517 Weld Specimen Dimensions and Crack Sizes (Intermediate).

S/N	T °C	a/W	P_m kN	t_f s	K_e MPa√m	J_e	J_p kJ/m²	J_c	K_k MPa√m	K_k/s MPa√m/s
W19	-70	0.49	9.1	0.21	151.5	107.3	52.8	160.1	185.1	881
W21	-70	0.48	7.9	0.24	129.6	78.4	87.7	166.2	188.6	786
W22	-70	0.50	8.2	0.18	137.1	87.8	22.1	109.9	153.4	852
W24	-70	0.50	8.1	0.16	134.2	84.2	17.1	101.3	147.2	920
W27	-70	0.50	8.2	0.17	135.4	85.6	16.9	102.5	148.1	871
W32	-70	0.54	7.8	0.22	149.9	105.1	39.8	144.9	176.1	800
W35	-70	0.50	7.8	0.16	131.5	80.8	9.8	90.6	139.2	870
W36	-70	0.50	9.7	0.22	160.5	120.3	70.9	191.2	202.2	919

Table B18 – A517 Weld Fracture Toughness Results (Intermediate).

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Appendix C

K_{Jc} Load-Load Line Displacement Curves

X80-A Plate

L-T Orientation
Intermediate Loading Rate

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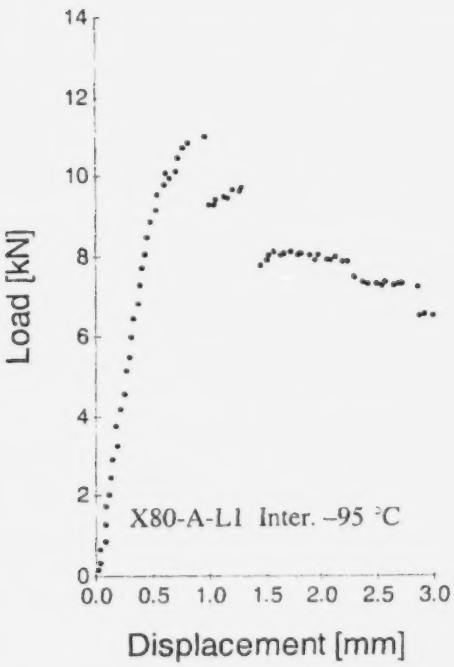

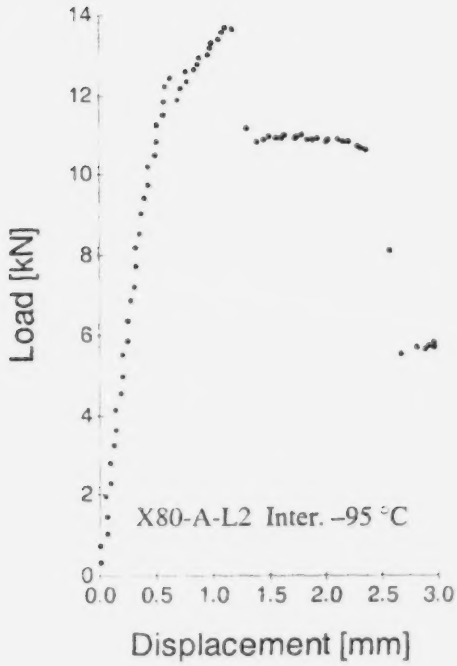

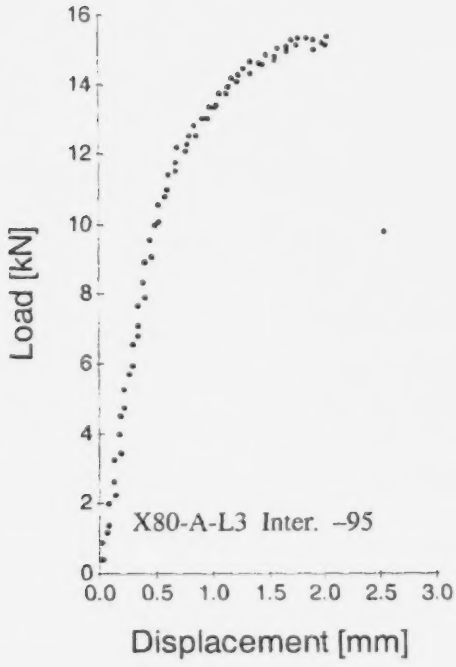

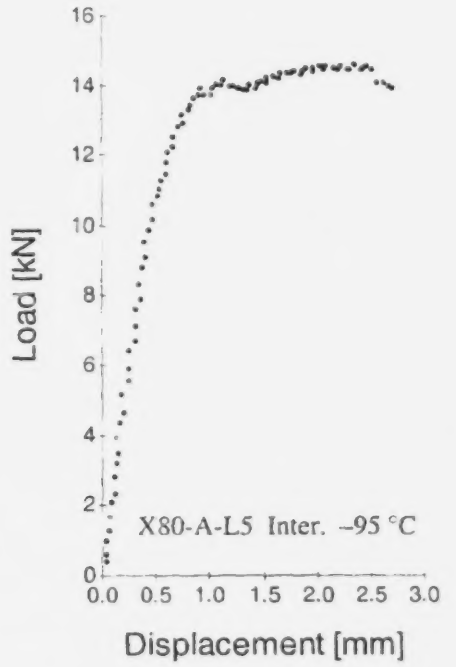

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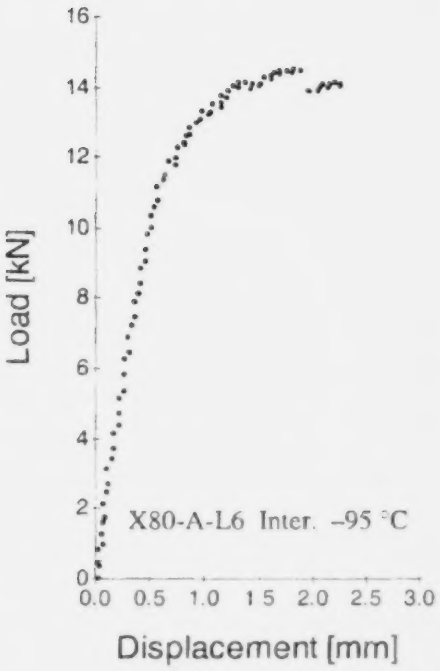

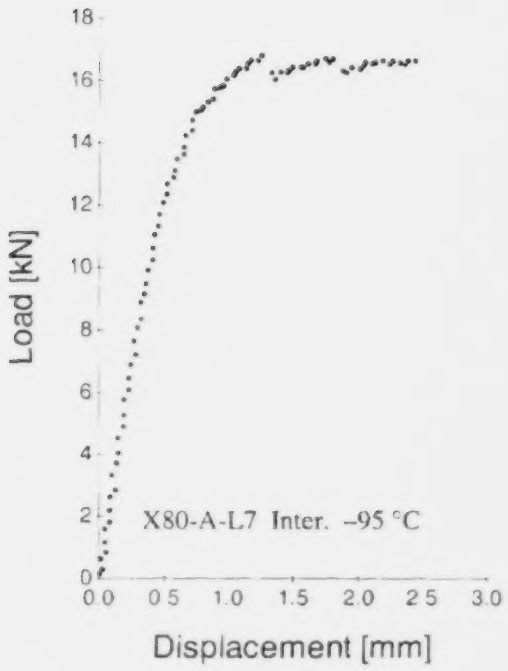

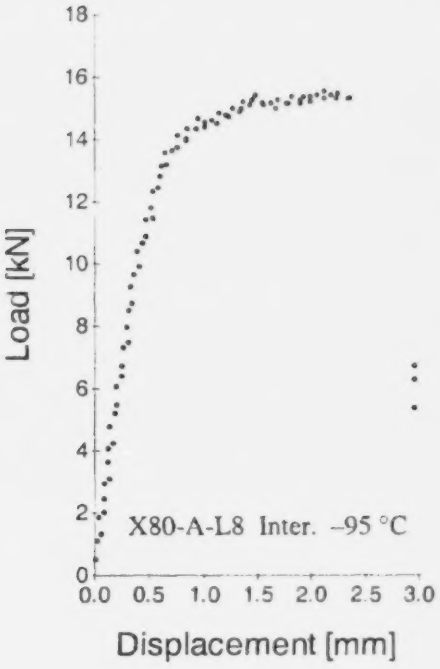

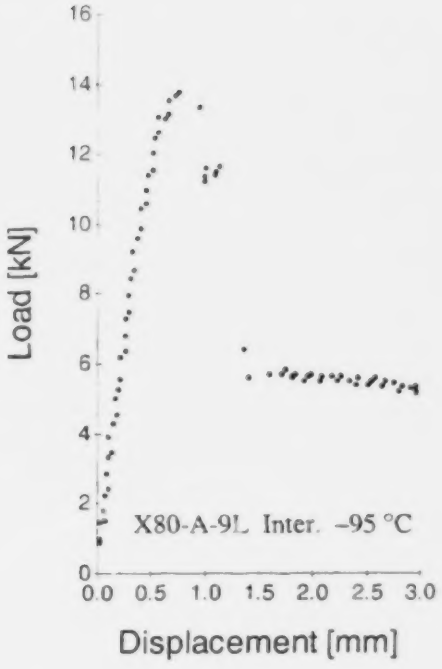

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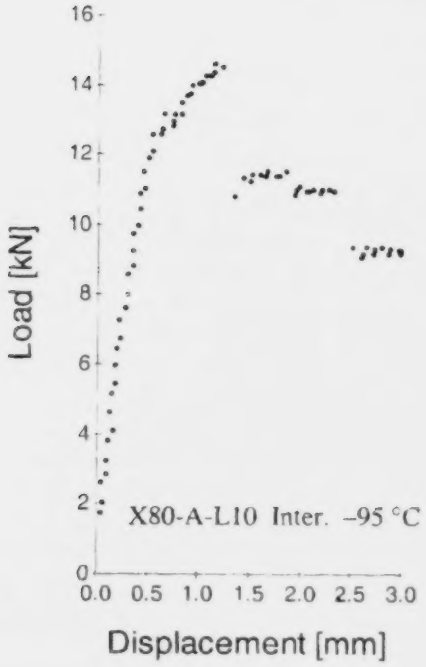

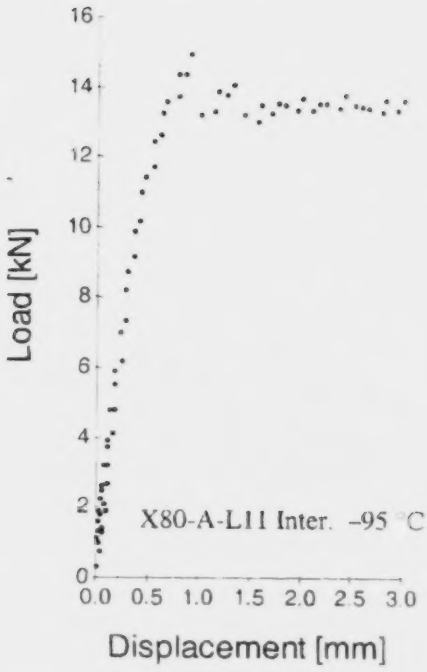

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Appendix D

K_{Jc} Load-Load Line Displacement Curves

X80-B Plate
T-L Orientation
Intermediate Loading Rate

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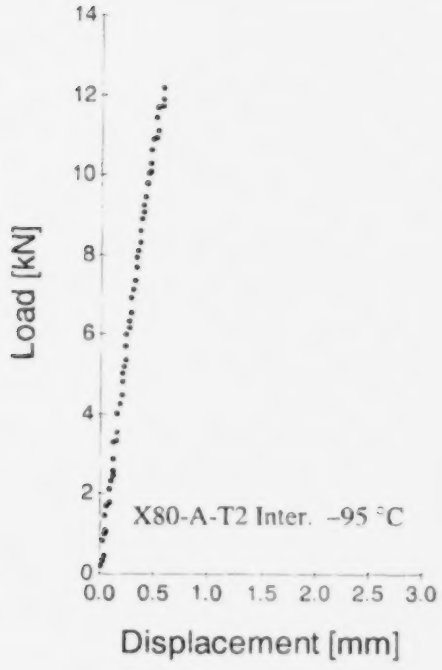

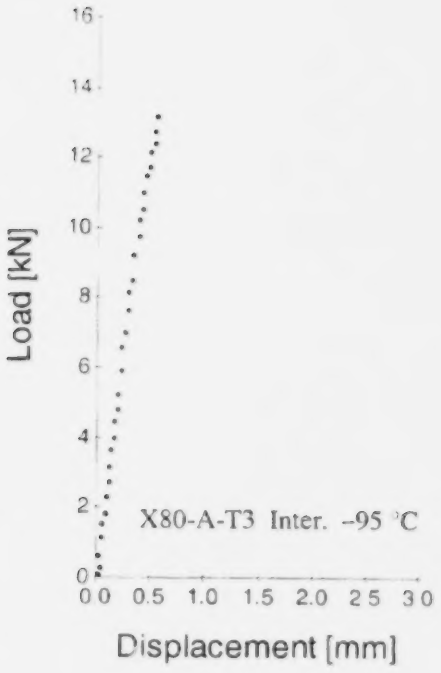

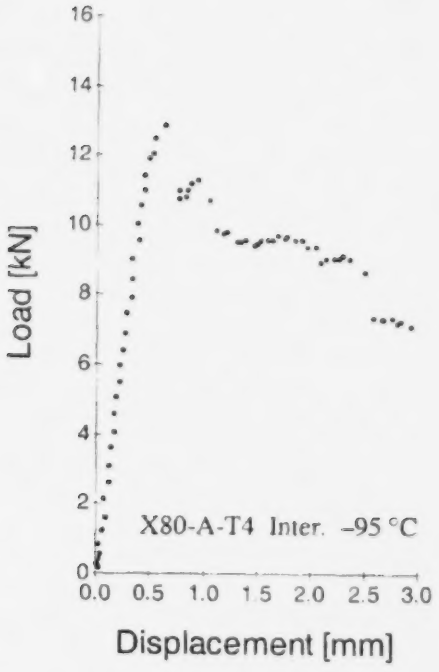

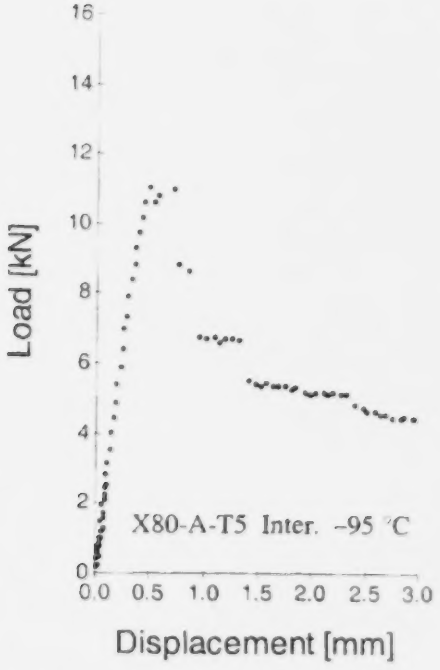

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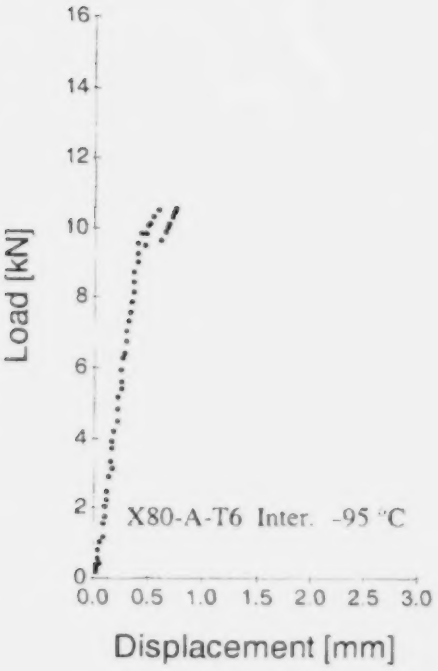

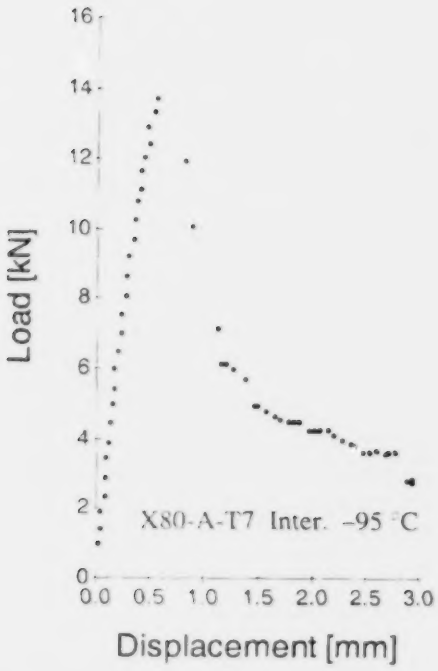

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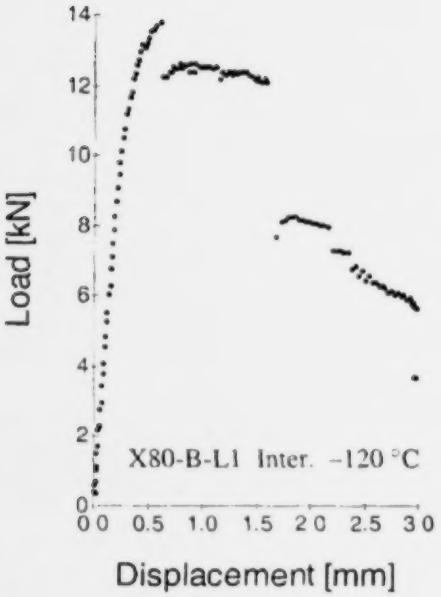
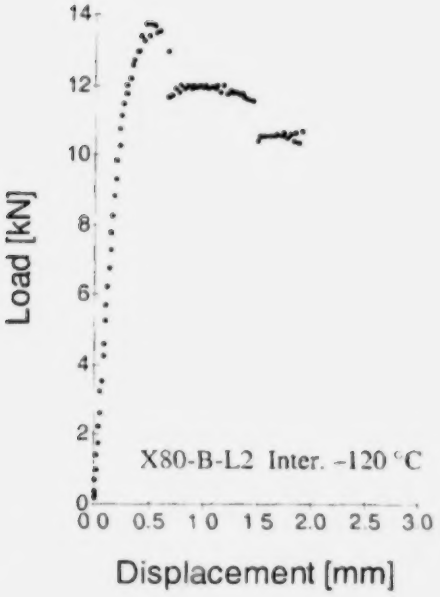
Appendix E

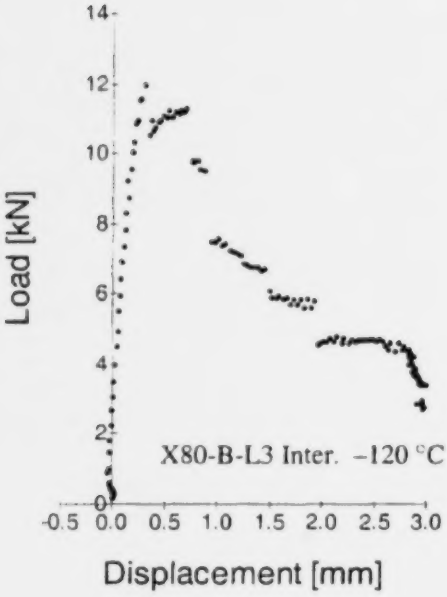
K_{Jc} Load-Load Line Displacement Curves

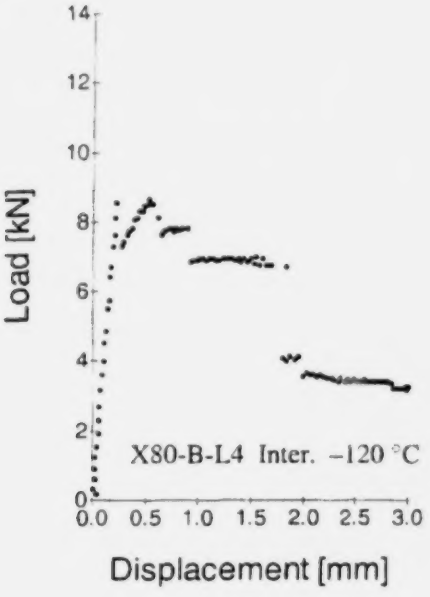
X80-B Plate
L-T Orientation
Intermediate Loading Rate

P517408.PDF [Page: 62 of 85]









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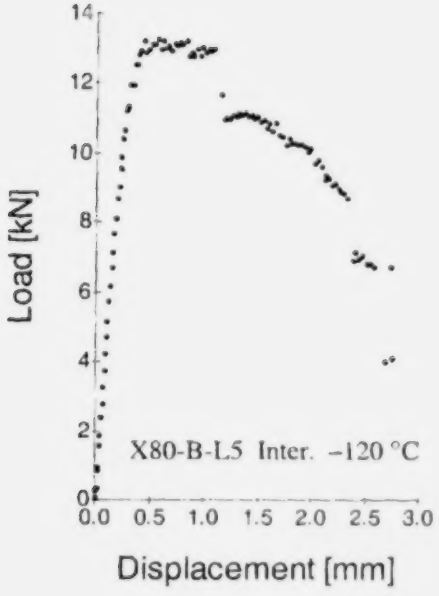

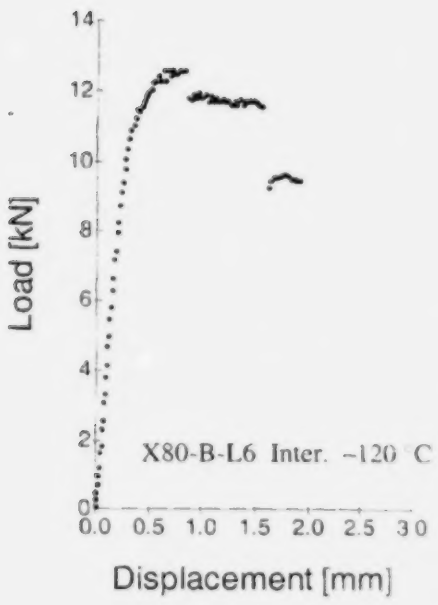

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Appendix F

K_{Jc} Load-Load Line Displacement Curves

X80-B Plate
T-L Orientation
Intermediate Loading Rate

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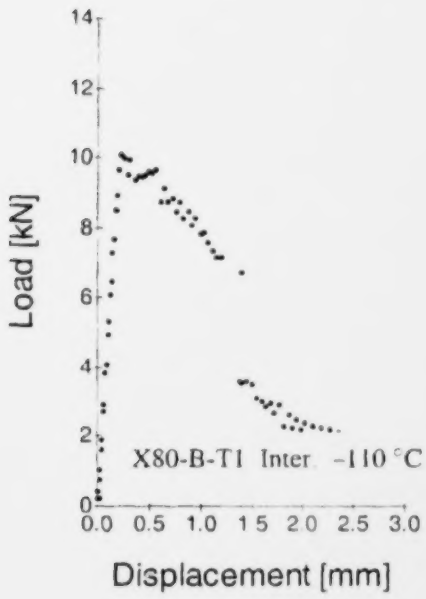

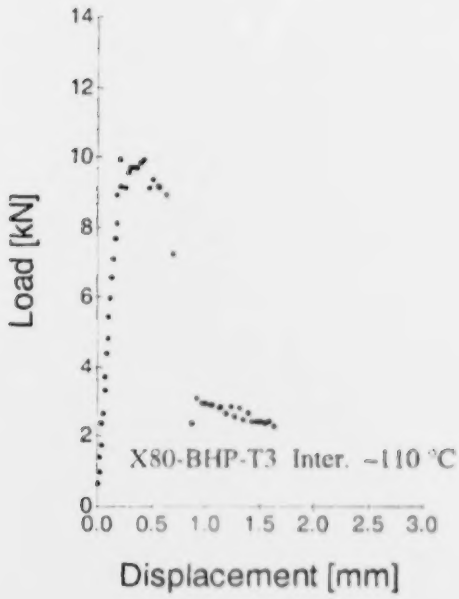

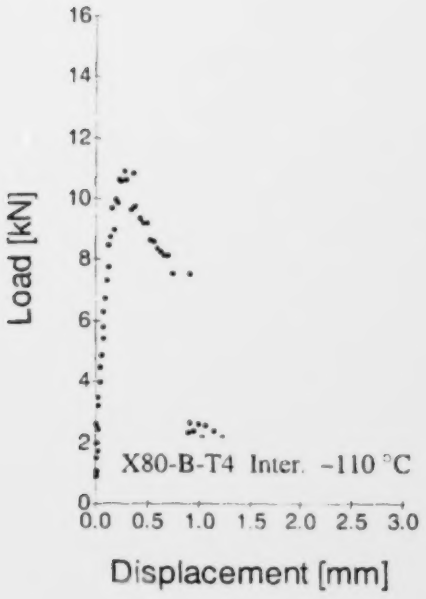

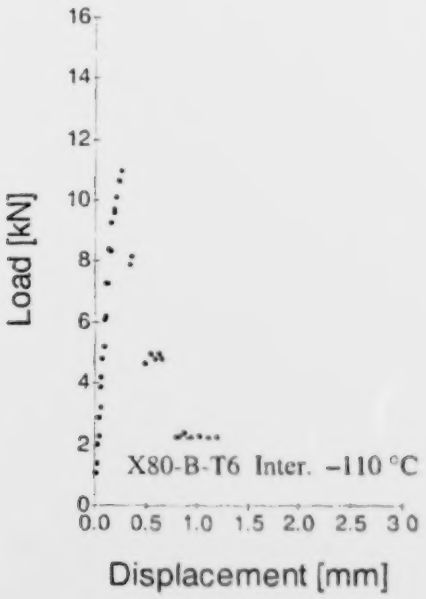

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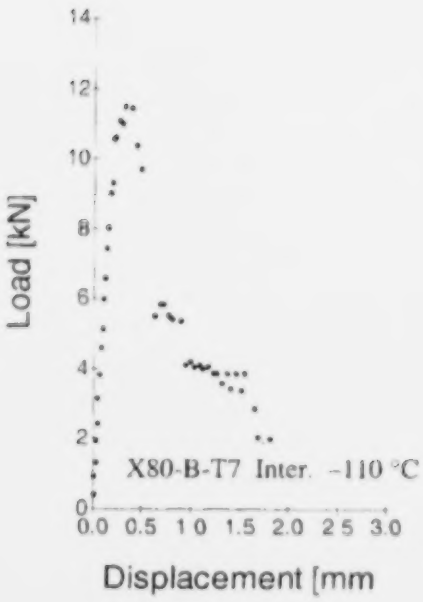

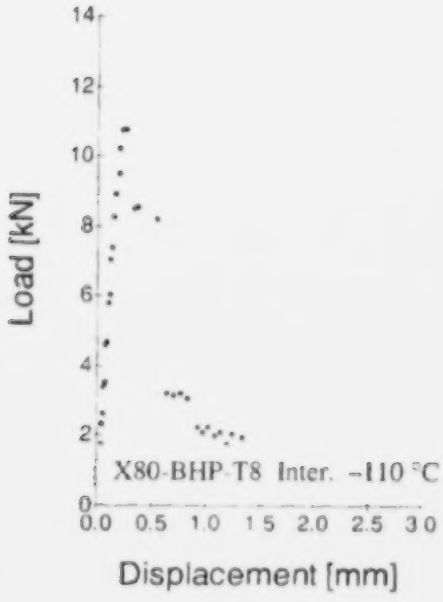

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Appendix G

K_{Jc} Load-Load Line Displacement Curves

A517 Plate
L-T Orientation
Intermediate Loading Rate

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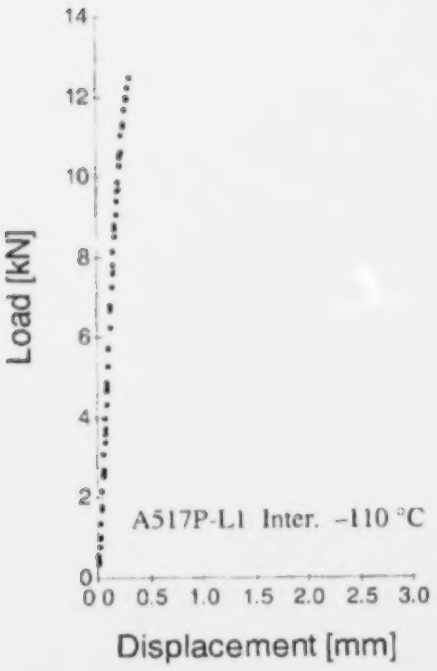

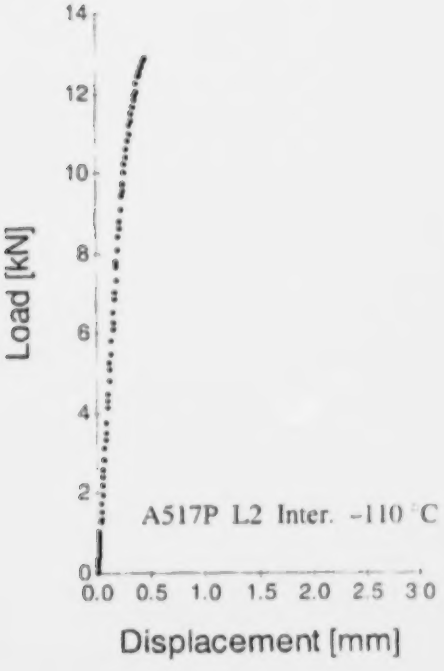

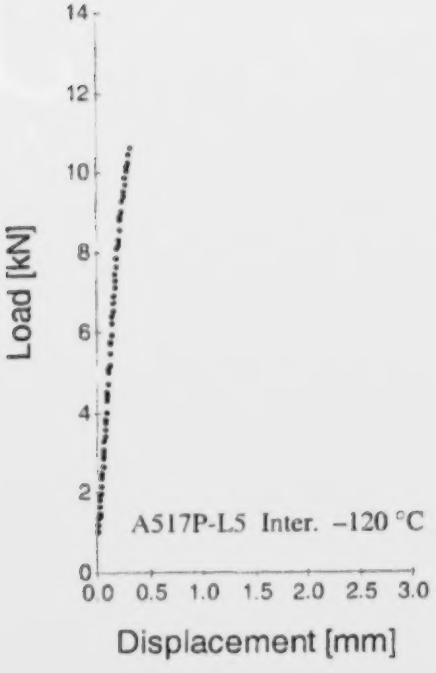

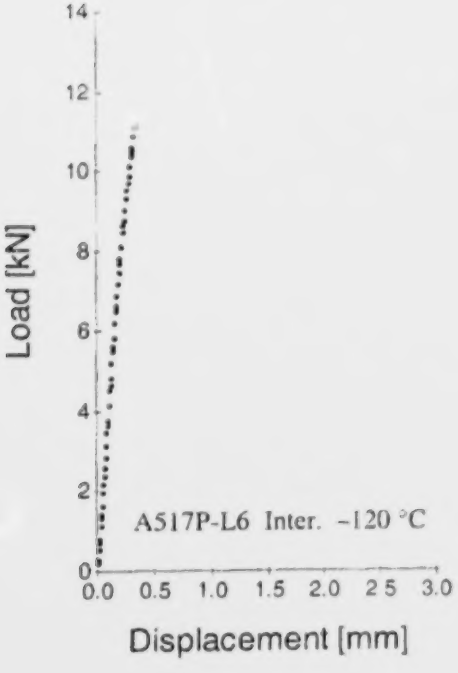

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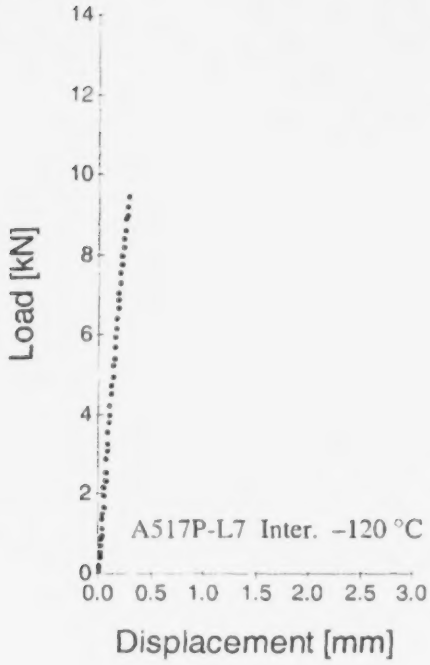

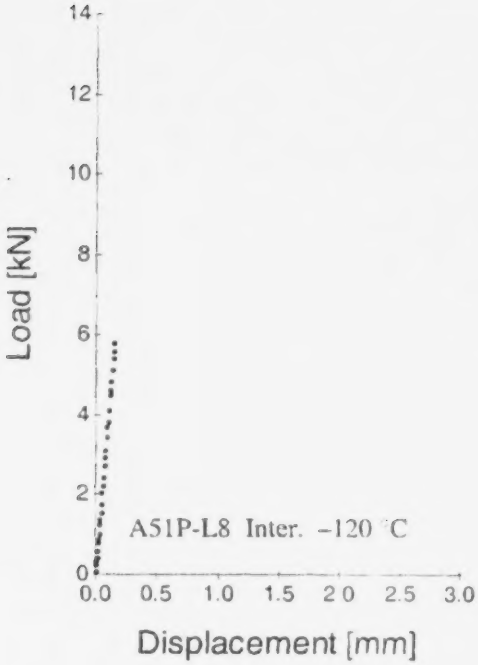

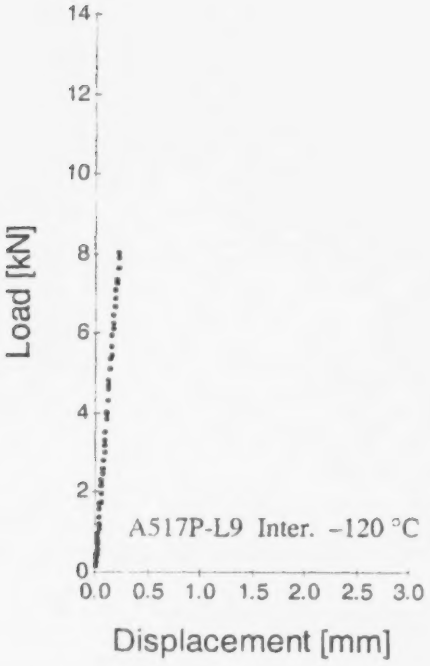

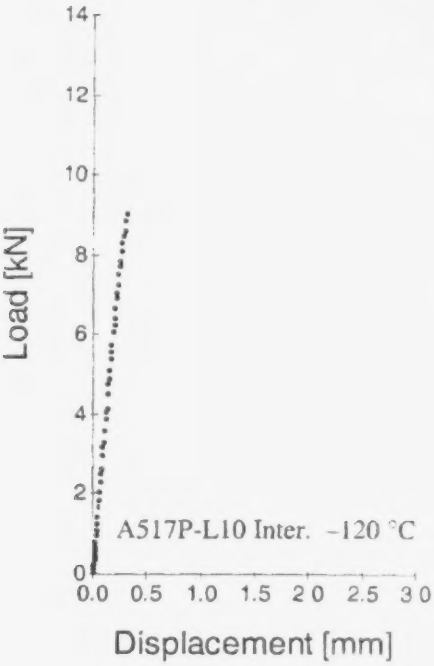

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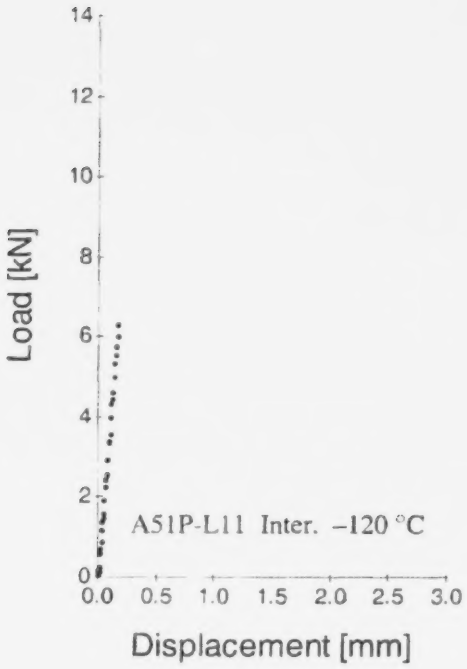

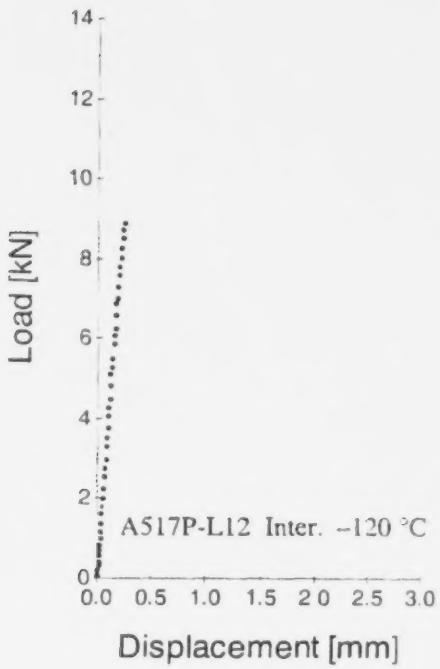

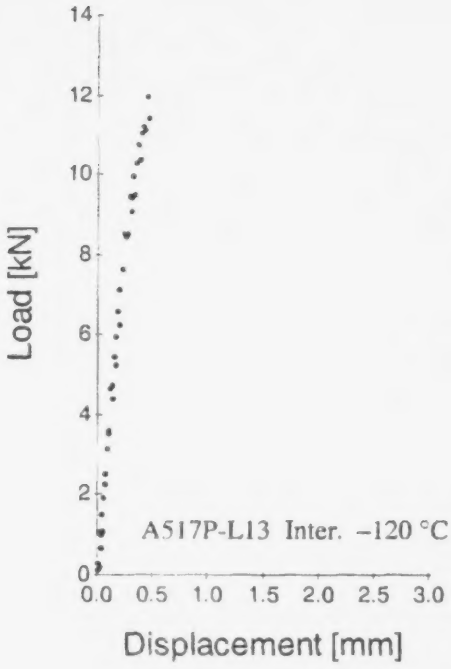

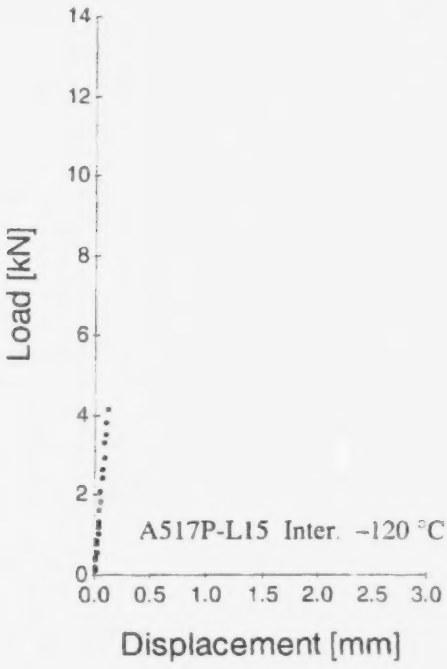

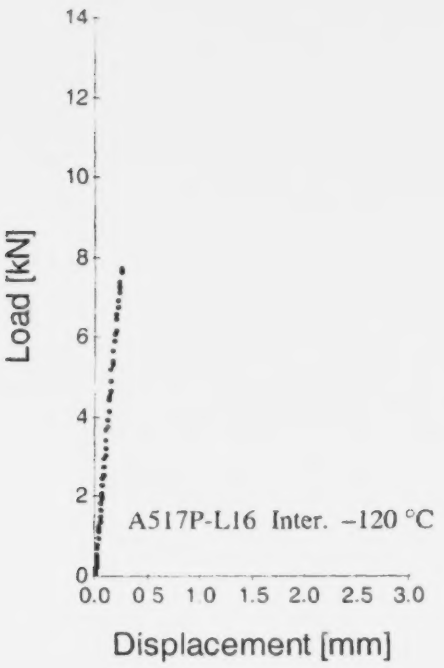
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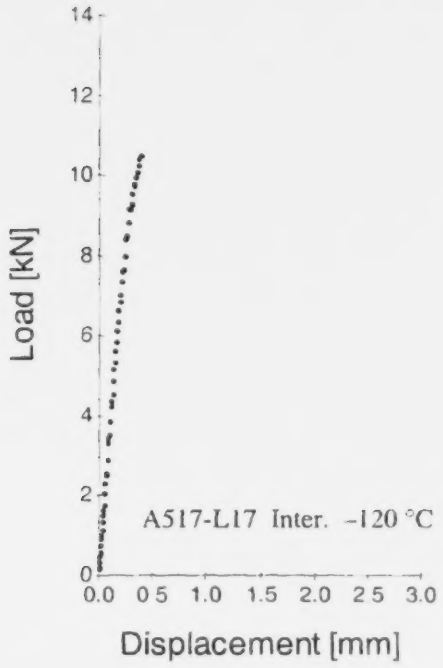
Displacement [mm]
A517P-L16 Inter. −120 °C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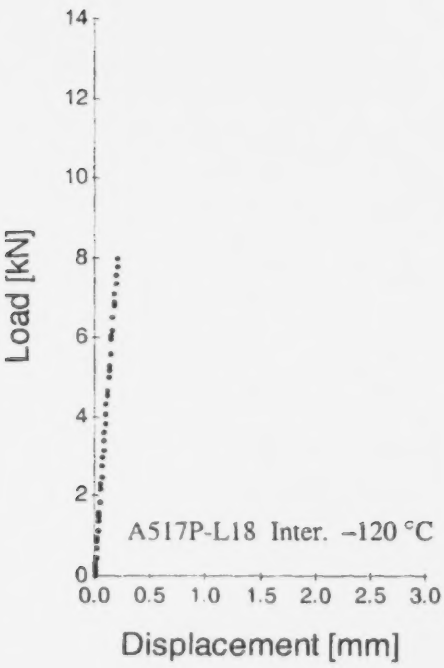
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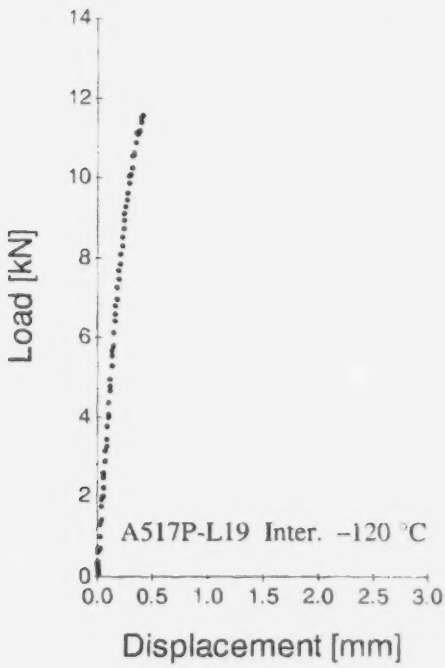
Load [kN]
Displacement [mm]
A517P-L19 Inter. −120 °C

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Appendix H

K_{Jc} Load-Load Line Displacement Curves

A517 Plate
T-L Orientation
Quasi-Static And Intermediate Loading Rates

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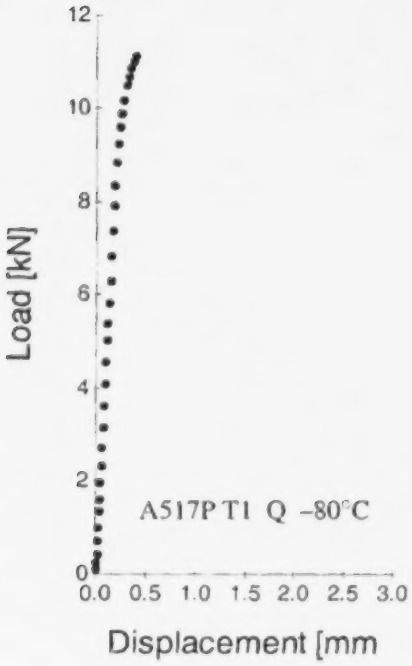

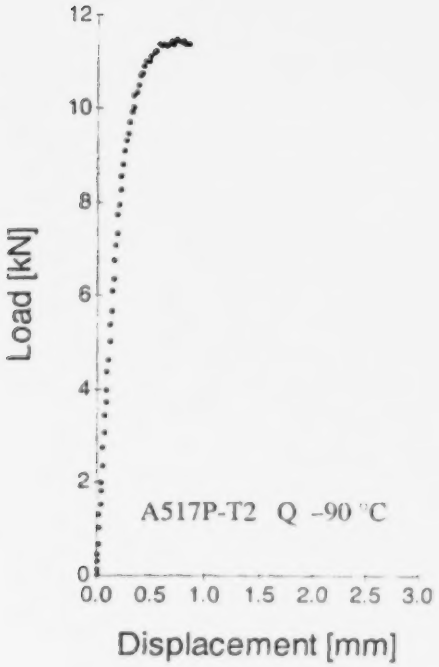

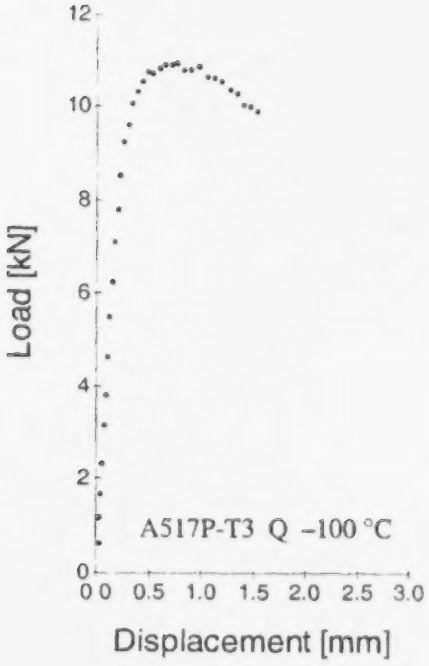

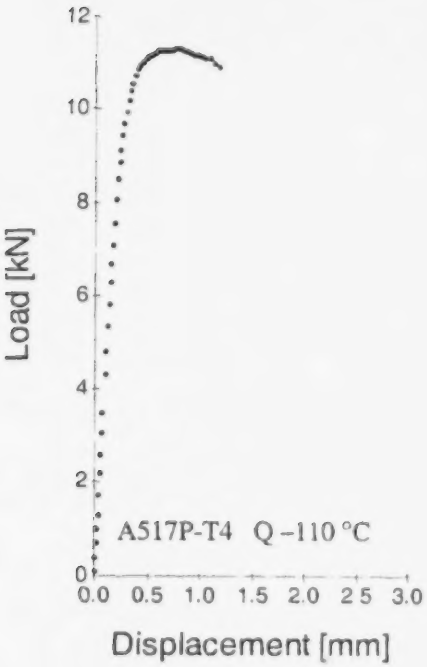

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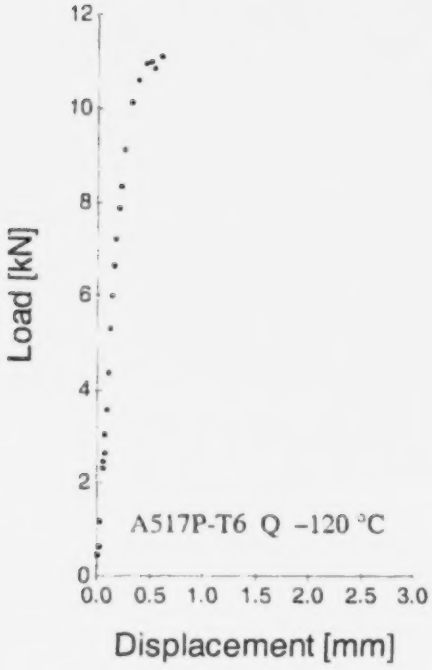

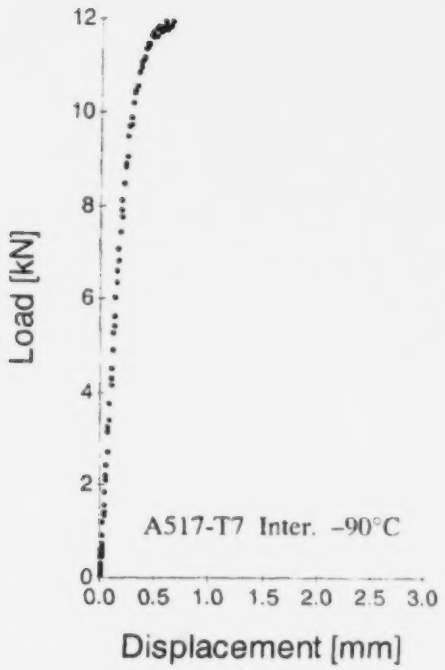

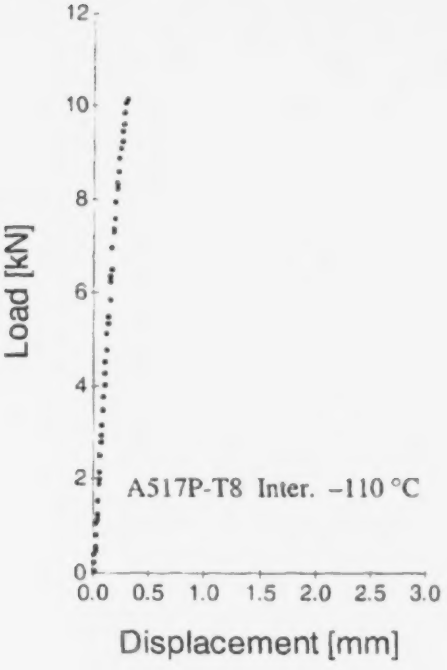

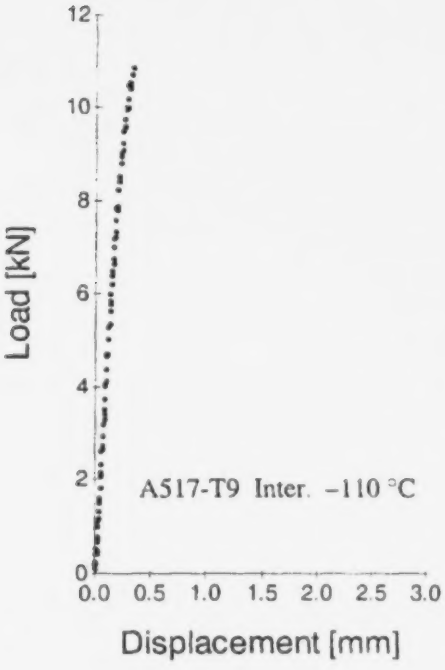

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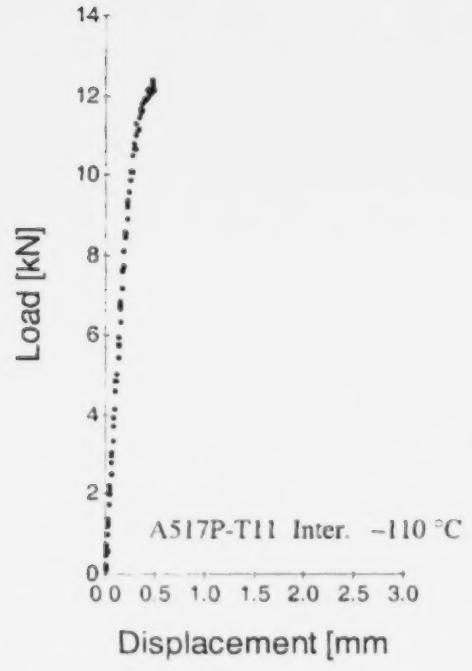

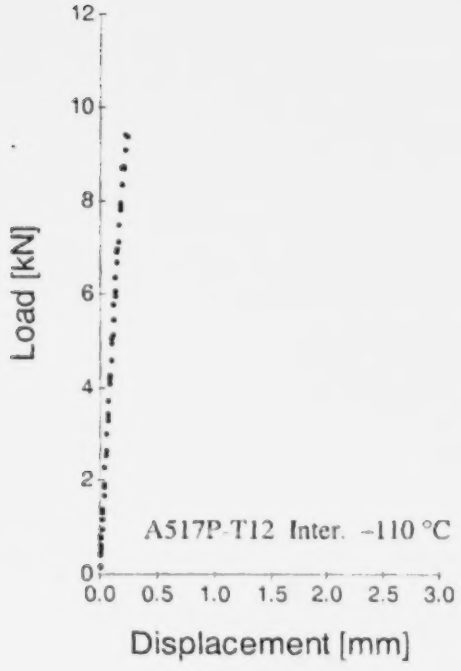

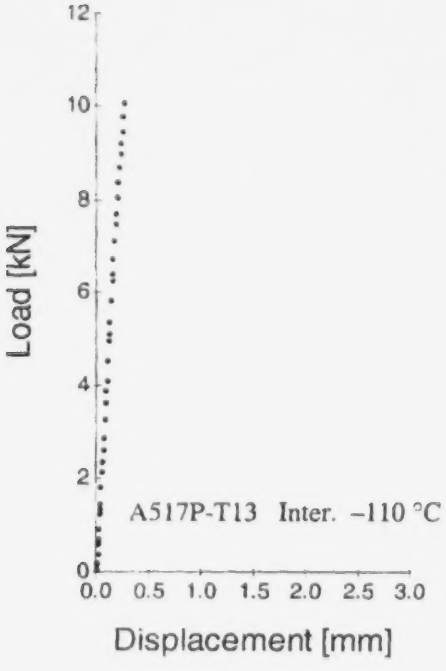

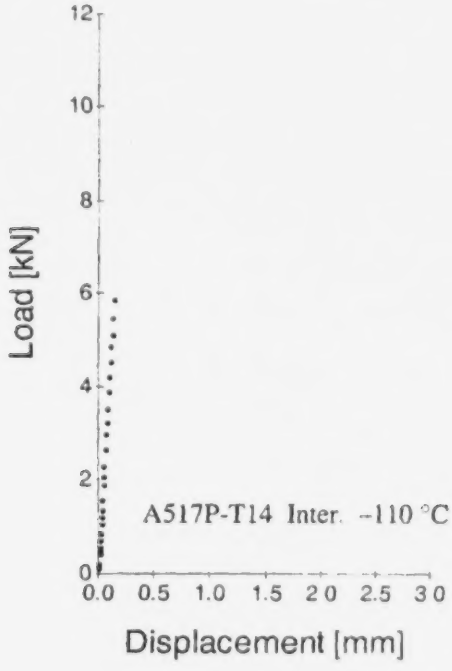

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Appendix I

K_{Jc} Load-Load Line Displacement Curves

A517 Weld
Quasi-Static Loading Rate

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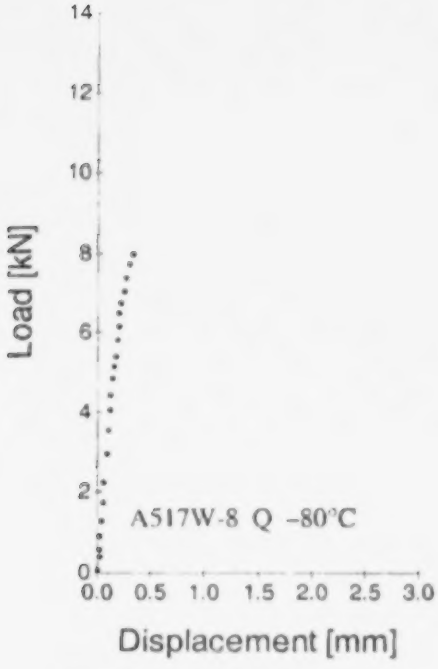

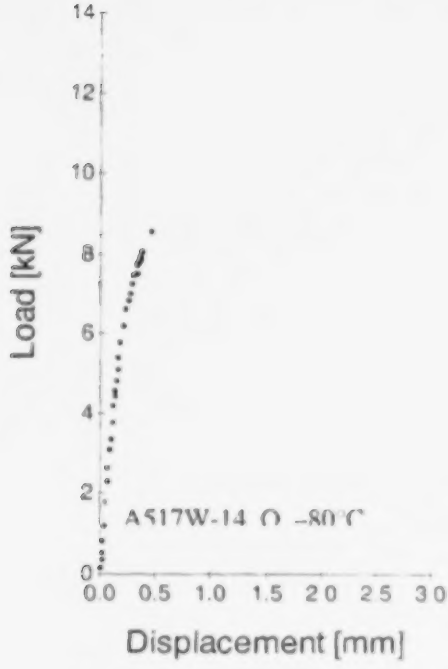

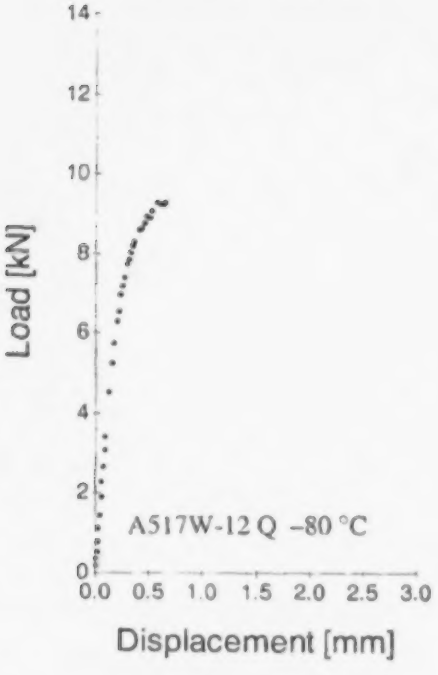

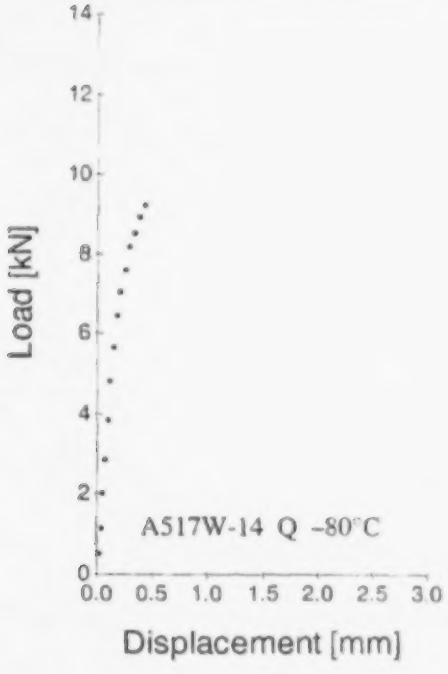

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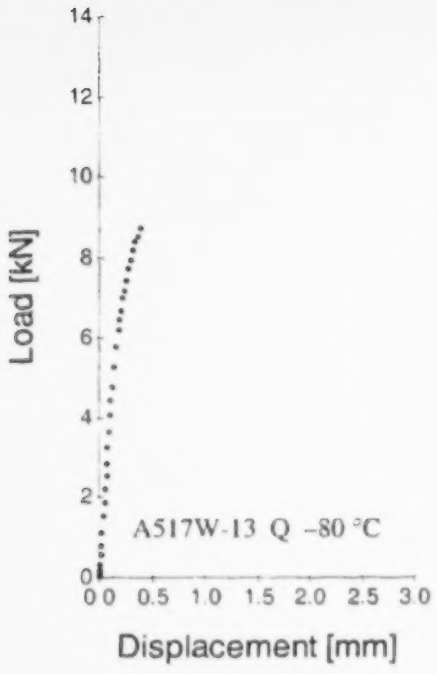

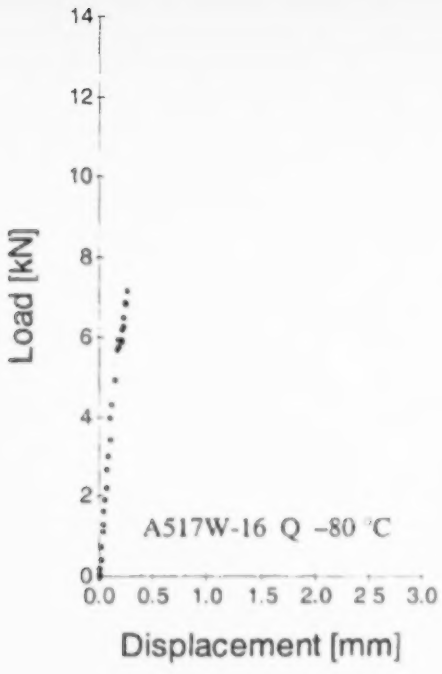

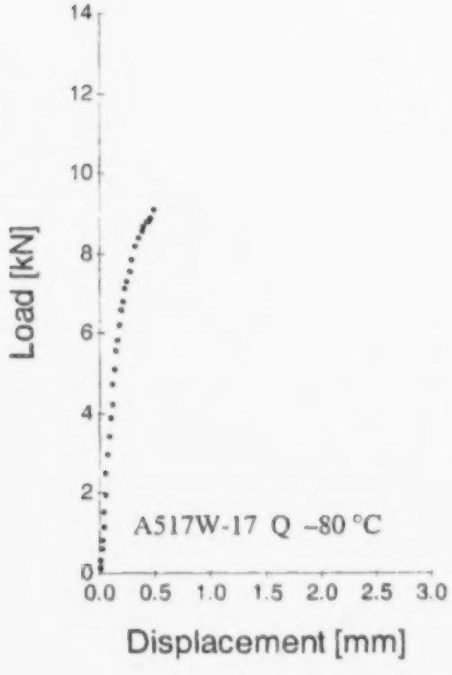

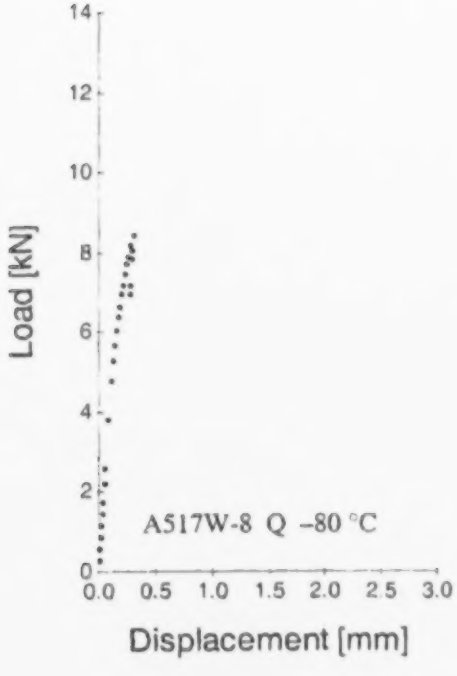

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Appendix J

K_{Jc} Load-Load Line Displacement Curves

A517 Weld
Intermediate Loading Rate

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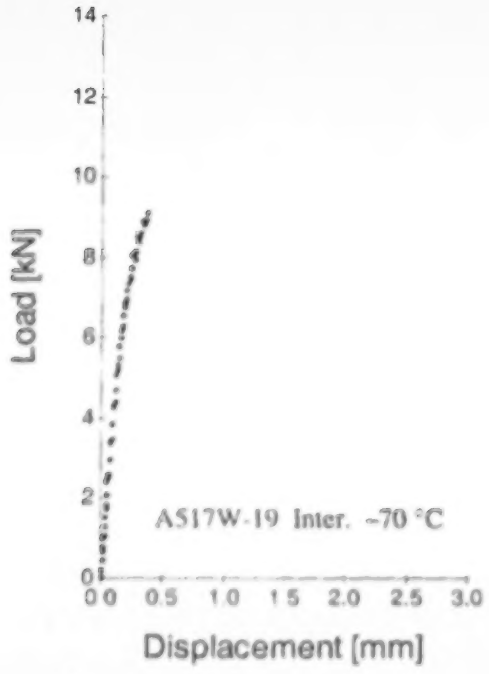

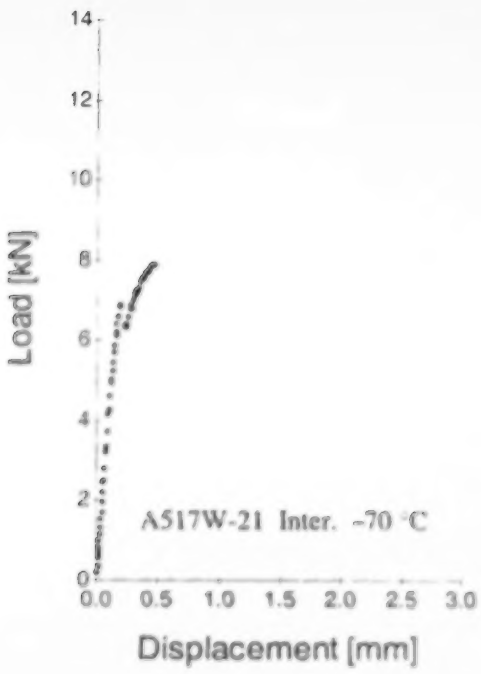

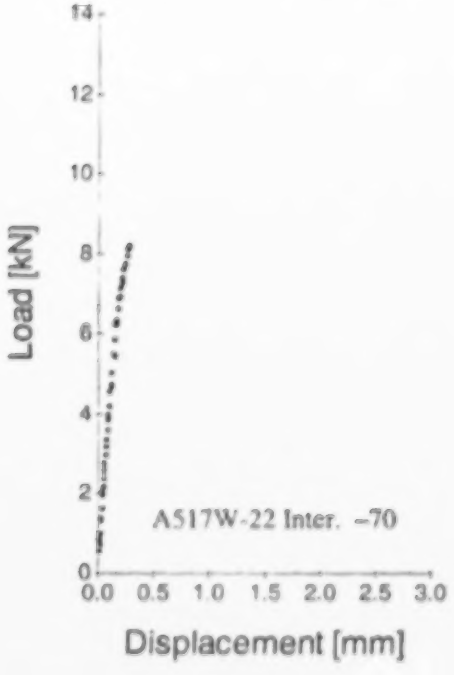

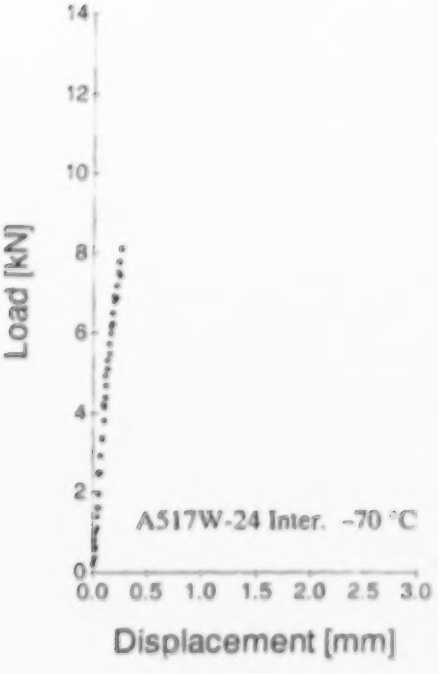

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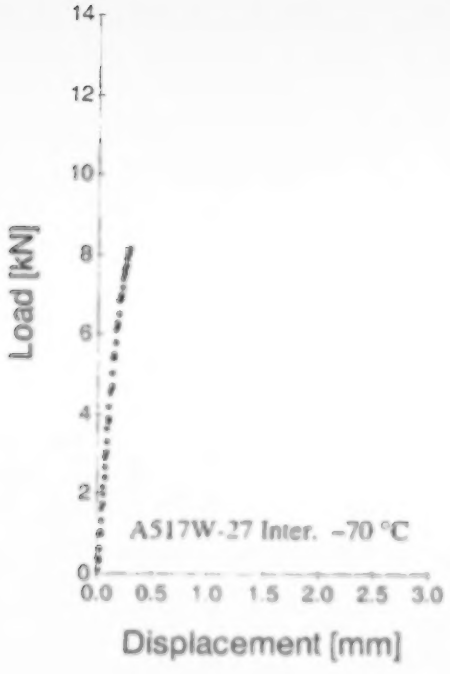

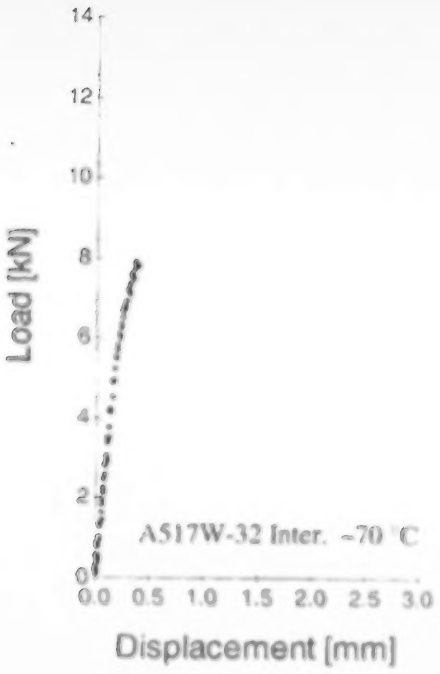

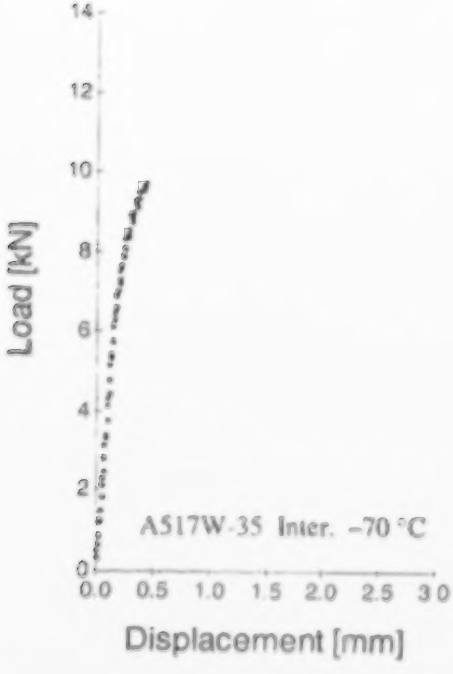

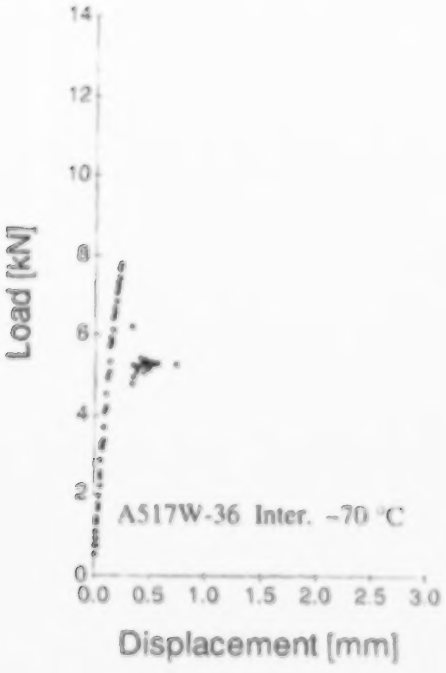

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This report describes the determination of reference temperatures for two steel plates and one weld, using ASTM Test Method E1921-97 "Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range" to generate transition master curves. Welded ASTM A517 steel is used in the Canadian Navy's Halifax class frigates, and both plate and a submerged arc weld have been tested in different orientations and at both quasi-static and intermediate loading rates. Plate samples of X80 steel from two different manufacturers have also been investigated. X80 steel is a candidate material for future use in the repair and construction of naval vesssels.

This work is being supplemented by experiments at the Dockyard Laboratory (Pacific) using a drop tower to achieve higher deformation rates. The test program has been successful in quantifying the fracture toughness over the temperature range of interest. The materials studied were very tough, and had very low reference temperatures, suggesting a high resistance to cleavage fracture.

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